Technical University of Denmark

Gear technical contributions to an ecosystem approach in the Danish bottom set nets fisheries

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Gear technical contributions to an Ecosystem Approach in the Danish bottom set nets fisheries

Ph.D. thesis by Esther Savina

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'So, after tens of thousands of years developing better techniques to catch fish, centuries of concern that such techniques may be causing significant damage to stocks and ecosystems, and half a century of realising that such impacts were occurring, the last two decades have seen a major change in focus in the field of fishing technology. This has occurred as scientists and fishers tried to develop techniques that permit the exploitation of fish stocks in a more sustainable manner.'

Kennelly and Broadhurst, 2002

PREFACE

The present thesis was submitted in partial fulfilment of the requirements for obtaining a Doctor of Philosophy (Ph.D.) degree. The thesis consists of a synopsis and four supporting papers. When submitted, one paper was published, two were in revision and one was a manuscript. The present version was updated on February 2018.

The work took place at DTU-Aqua in the section for Ecosystem based marine management in the fisheries technology group based in Hirtshals from December 2013 to April 2017 under the supervision of Ludvig Ahm Krag (initially Niels Madsen) and co-supervision of Finn Larsen (initially Rikke P. Frandsen and Ludvig Ahm Krag).

The thesis was defended on June 8th 2014, and examined by Ole Ritzau Eigaard (DTU-Aqua), Marie-Joëlle Rochet (IFREMER) and Barry O'Neill (Marine Scotland Science).

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LIST OF PAPERS

Paper I

Effect of fisher's soak tactic on catch pattern in the Danish gillnet plaice fishery

Status: published in Fisheries Research (in revision when the thesis was submitted and defended)

Savina, E., Krag, L.A., Frandsen, R.P., Madsen, N., 2017. Effect of fisher's soak tactic on catch pattern in the Danish gillnet plaice fishery. Fisheries Research, 196, 56-65.

Paper II

Discard of regulated species under the landing obligation in the Danish bottom set nets fisheries for cod, sole and plaice in the North Sea

Status: manuscript

Paper III

Testing the effect of soak time on catch damage in a coastal gillnetter and the consequences on processed fish quality

Status: published in Food Control

Savina, E., Karlsen, J.D., Frandsen, R.P., Krag, L.A., Kristensen, K., Madsen, N., 2016. Testing the effect of soak time on catch damage in a coastal gillnetter and the consequences on processed fish quality. Food Control, 70, 310-317.

Paper IV

Developing and testing a computer vision method to quantify 3D movements of bottom-set gillnets on the seabed

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Savina, E., Krag, L.A., Madsen, N. Developing and testing a computer vision method to quantify 3D movements of bottom-set gillnets on the seabed. ICES Journal of Marine Research, 2017, fsx194, https://doi.org/10.1093/icesjms/fsx194

RESUMÉ (Dansk)

EU er i gang med at implementere rammer for bæredygtig fiskeriforvaltning indenfor Økosystem Baseret Fiskeri med hovedvægt på målene i havstrategi rammedirektivet og den fælles fiskeripolitik (landings forpligtelsen). Da fiskeri kan påvirke andre komponenter og ikke kun målarter, med eksempelvis fysiske skader på fiskehabitater eller udsmid af uønskede fiskearter, skal økosystemet som helhed vurderes. Selve fiskeriflåden er blevet reduceret siden midten af 1990'erne, men garn og toggegarn repræsenterer stadig omkring 80 % af den danske fiskeriflåde i antal fartøjer. Garn og toggegarn har den fordel, at energiforbruget er ret lavt og der opnås god selektivitet. Imidlertid **er der begrænset viden om påvirkningen af bundsatte garn på økosystemet**. Fokus blev lagt på metodeudvikling (Artikel **IV**), **fangstmønstre** (Artikel **I, II** og **III**) og **habitatpåvirkninger** (Artikel **IV**). Hvad angår fangstmønstre kan man have til hensigt at minimere den uønskede fangst (artikel **I** og **II**), eller maksimere den ønskede fangst, f.eks. ved at justere **fiskeritaktik** (Artikel **I**) eller ved at forbedre **fangstkvaliteten** på målarterne (Artikel **III**).

De begrænsede oplysninger om passive redskaber skyldes til dels historisk fokus på aktive redskaber, men også fordi dataindsamling og dataanalyse kræver **udvikling af passende, innovative metoder** til at vurdere den nye informationstype, der skal indsamles som led i en økosystembaseret tilgang til fiskeriet. En stereo billeddannelsesmetode til in situ vurdering af den dynamiske bevægelse af passive redskaber (Artikel **IV**) blev identificeret, tilpasset, testet og anvendt. At sammenligne fiskerier med bundsatte garn kan være en udfordring, da målingen af fiskeriindsatsen afhænger af forskellige faktorer, såsom kombinationen af fiskenettets egenskaber, netlængde, eller garnets sættetid i havet. Statistiske metoder, der for nylig er blevet udviklet, blev identificeret og anvendt til estimering af den relative fangsteffektivitet mellem to forskellige design af et passivt fiskeredskab (Artikel **I**), eller til at standardisere data til en bred vifte af indsatsvariabler ved at inkludere den landede del af fiskeriet med anvendelse af udsmidsandel (Artikel **II**).

Fiskeriteknologer kan spille en central rolle i at søge efter win-win løsninger, så fiskeriet kan fortsætte på en økologisk bæredygtig måde, nemlig at undgå uønsket fangst og at undgå at påføre skader på habitater. Garns selektive egenskaber kan forbedres ved at ændre redskabets karakteristikker, f.eks. maskestørrelse eller garnmateriale, men i mange tilfælde spiller fiskernes operationelle taktik en dominerende rolle, da nye selektive teknologier som involverer mere komplekse redskaber sædvanligvis er begrænset i passivt fiskeri. Fiskeriteknologiske overvejelser, dvs. redskabsdesign og operationel taktik, kan være med til at implementere en økosystembaseret tilgang til det danske bundsatte garnfiskeri. Virkningerne af redskabsdesign, f.eks. lette eller tunge net, på habitat (Artikel **IV**), og fiskernes taktik, dvs. ståtid eller valg af ønskede fiskearter, på fangstmønstre og kvalitet blev undersøgt (Artiklerne **I**, **II** og **III**).

I **Artikel I** blev effekten af fiskernes ståtidstaktik på fangstmønstre i det danske garnfiskeri efter rødspætter undersøgt ved at estimere den længdebaserede fangsteffektivitet, eller relativ størrelsesselektivitet på tre forskellige ståtidsmønstre, dvs. 12 timer om dagen, 12 timer om natten og 24 timer. Ved at justere fiskernes ståtidstaktik, f.eks. til 12 timer om dagen, kan fiskere, der deltager i det kystnære sommerfiskeri efter rødspætter, maksimere deres fangst ved at fange flere rødspætter på kommerciel størrelse, når de er mere tilgængelige for redskabet, og begrænse håndteringstiden ved at fange færre isinger og krabber, når de er mindre tilgængelige for redskabet.

I **Artikel II** blev discard mængden mellem regulerede fiskearter i henhold til landings forpligtelser indenfor dansk bundsat garnfiskeri efter torsk, rødspætte og tunge i Nordsøen beskrevet ud fra de discard data, der er indhentet af observatører på havet, samt effekten af garnets sættetid, dybde, bredde- og længdegrad blev undersøgt ved anvendelse af en betafordeling. Discard mængden varierede mellem 1.10 og 100 % med høj variabilitet mellem fiskeri, arter og fiskepladser. Discard af undermålsfisk, hvor der er anvendt små maskestørrelser ved tungefiskeri er den vigtigst identificerede udfordring. I torskefiskeriet i Nordsøen der var en reduceret sandsynlighed for discard af torsk med øget dybde, med størst effekt i de senere år.

I **Artikel III** blev en stereo billeddannelsesmetode identificeret, tilpasset, testet og anvendt til in situ kvantificering af bevægelsen af blylinen til lette og tunge garn, indsat på bunden på sandede habitater ved at bruge det danske kystnære garnfiskeri som case study. Den direkte fysiske forstyrrelse af havbunden af garn var minimal, da blylinens bevægelse ikke trængte ned i havbunden. Den generelle opfattelse er at tungt fiskeudstyr er mere ødelæggende for habitater, men det blev påvist her, at lette garn bevæger sig signifikant mere end tunge.

I **Artikel IV** blev effekten af ståtid (12 og 24 timer) på fangstkvalitet undersøgt, samt om de registrerede skader på hele fisk har en effekt på forarbejdede produkter såsom fileter, undersøgt om bord på et kystnært garnfiskerfartøj og på en specialiseret forarbejdningsfabrik. Det var signifikant mere sandsynligt at få skader på hele fisk end på fileterede fisk, og signifikant mere sandsynlig længere ståtider. Med den optimale ståtid kan garn levere fisk af en god kvalitet.

ABSTRACT (English)

The European Union is implementing a sustainable fisheries management framework called the Ecosystem Approach to Fisheries, with the main basis provided in the objectives of the Marine Strategy Framework Directive and the Common Fishery Policy (landing obligation). As fishing can affect other components and not just targeted species, with for example physical damage to habitats or discarding of non-target species, the ecosystem as a whole must be considered. Although the fleet has reduced since the mid-1990s, gill- and trammel nets still represent about 80% of the Danish fleet in number of vessels. Gill- and trammel nets have the advantage of low energy consumption and good size selectivity. However, there is **limited knowledge about the ecosystem effects of bottom set nets**. Focus was given to methodological development (Paper **IV**), **catch pattern** (Papers **I**, **II** and **III**) and **habitat effects** (Paper **IV**). Regarding catch pattern, one can intend to minimize the catch that is unwanted (Papers **I** and **II**), or to maximize the part of the catch that is wanted, e.g., by adjusting the **fishing tactic** (Paper **I**) or by improving **catch quality** of the target species (Paper **III**).

The limited information on passive gears is partly due to historical focus on active gears, but also because data collection and analysis calls for the **development of appropriate innovative assessment methodologies** to properly assess the new type of information which has to be gathered as part of an Ecosystem Approach to Fisheries. A stereo imaging method to assess in-situ the dynamic behavior of passive gears was identified, adapted, tested and used (Paper **IV**). Comparing bottom set nets fishing operations can be challenging as the measure of fishing effort depends on various factors such as the combination of netting characteristics, net length, or soak time. Statistical methods that have recently been developed were identified and used for estimating the relative catch efficiency between two different designs of a passive fishing gear (Paper **I**) or to standardize data to a wide range of effort variables by including the landed portion of the fishing operation with the use of discard ratios (Paper **II**).

Gear technologists can play a key role in searching for win-win solutions so that fishing can continue in an ecologically sustainable manner, i.e., avoiding unwanted catch and habitat damage. The selection properties of gillnets may be improved by changing the gear characteristics, e.g., mesh size or netting material, but in many cases the fisher's operational tactic plays a preponderant role, as new selective technologies involving more complex gear are usually limited in passive fisheries. Gear technological considerations, i.e., **gear design and operational tactics**, can help to implement an Ecosystem Approach to the Danish bottom set nets fisheries. The effects of gear design, i.e., light and heavy nets, on habitat effects (Paper **IV**) and fisher's tactic, i.e., soak duration or choice of target species, on catch pattern and quality (Papers **I**, **II** and **III**) were explored.

In **Paper I**, the effect of fisher's soak tactic on catch pattern in the Danish gillnet plaice fishery was investigated by estimating the length-dependent catch efficiency, or relative size selectivity, of three different soak patterns, i.e., 12h at day, 12h at night and 24h. By adjusting their soak tactic, i.e., 12h at day, fishers participating in the costal summer fishery for plaice can maximize their catch by catching more plaice at commercial size when they are more available to the gear, and limit handling time by catching less dab and crabs when they are less available to the gear.

In **Paper II**, discard ratios of regulated fish species under the landing obligation in the Danish bottom set nets fisheries for cod, plaice and sole in the North Sea were described using the discard data from observers at sea, and the effects of soak duration, depth, latitude and longitude on discards were investigated by the use of a beta distribution. Discard ratios ranged from 1.10 to 100%, with high variability between fishing operations, species and fisheries, discard of undersized individuals due to the use of small mesh sizes in the sole fishery being the main challenge identified. In the North Sea cod fishery, there was a decreased probability of cod discard with depth, with greater effect in the more recent years.

In **Paper III**, the effect of soak time (12 and 24h) on catch quality, as well as if the registered damages on whole fish have an effect on processed products such as fillets, were investigated aboard a coastal gillnetter and at a specialized processing factory. Damage in fish was significantly more likely for whole than filleted fish, and significantly more likely for longer soak times. With the optimum soak time, gillnets can deliver good quality fish.

In **Paper VI**, a stereo imaging method was identified, adapted, tested and used to quantify in-situ the movement of the leadline of light and heavy gillnets, deployed on the bottom in sandy habitats, using the Danish gillnet coastal plaice fishery as a case study. The direct physical disruption of the seabed of gillnets was minimal as the leadline was moving but not penetrating into the seabed. Whereas the general perception is that heavy gears are more destructive to the habitat, it was demonstrated here that light nets were moving significantly more than heavy ones.

ABBREVIATIONS

CCTV	Closed Circuit TV
CDi	Catch-damage-index
CFP	Common Fisheries Policy
EAF	Ecosystem Approach to Fisheries
EC	European Commission
EU	European Union
FO	Fishing Operation
GES	Good Environmental Status
ICES	International Council for the Exploration of the Sea
ITQ	Individual Transferable Quota
MCRS	Minimum Conservation Reference Size
MLS	Minimum Landing Size
MSFD	Marine Strategy Framework Directive
STECF	Scientific, Technical and Economic Committee for Fisheries
TAC	Total Allowable Catch

SPECIES SCIENTIFIC NAMES

Cod	*Gadus morhua*	Pollack	*Pollachius pollachius*
Dab	*Limanda limanda*	Monkfish	*Lophius piscatorius*
Edible crab	*Cancer pagarus*	Northern prawn	*Pandalus borealis*
Flounder	*Platichthys flesus*	Norway lobster	*Nephrops norvegicus*
Haddock	*Melanogrammus aeglefinus*	Saithe	*Pollachius virens*
Hake	*Merluccius merluccius*	Sole	*Solea solea*
Harbour porpoise	*Phocoena Phocoena*	Turbot	*Psetta maximus*
Plaice	*Pleuronectes platessa*	Whiting	*Merlangius merlangus*

I. INTRODUCTION

A. Ecosystem Approach to Fisheries

1. Definition

Fisheries have traditionally been managed with focus on single target species (Pikitch *et al.*, 2004; Godø, 2009; Bellido *et al.*, 2011; Ramírez-Monsalve *et al.*, 2016). But with the collapse of some fish stocks, the need for a better understanding of ecosystem functioning has emerged (Pikitch *et al.*, 2004; Ramírez-Monsalve *et al.*, 2016). The idea that target species should be managed in the context of the overall state of the system, including habitat, non-target species and the human dimensions of fisheries, has led to a change in the paradigm of fisheries management (Pikitch *et al.*, 2004; Bellido *et al.*, 2011). The ecosystem approach promotes a management regime that maintains the health of the ecosystem together with appropriate human use of the environment for the benefit of current and future generations (Garcia and Cochrane, 2005). The application of the ecosystem approach to fisheries has been given various names and definitions, including Ecosystem Based Fisheries Management (EBFM), Ecosystem Approach to Fisheries Management (EAFM) and Ecosystem Approach to Fisheries (EAF). These terminologies refer to approaches with overlapping objectives, but reflect the relative importance given respectively to fisheries objectives and to ecosystem conservation in their interpretation (Garcia, 2003).

The Reykjavik FAO Expert Consultation held in 2003 agreed to define the EAF as follow: “an ecosystem approach to fisheries strives to balance diverse societal objectives, by taking account of the knowledge and uncertainties about biotic, abiotic and human components of ecosystems and their interactions and applying an integrated approach to fisheries within ecologically meaningful boundaries” (Garcia, 2003).

The 2013 revision of the European Union (EU) Common Fishery Policy (CFP) explicitly defines the ecosystem-based approach to fisheries management as “an integrated approach to managing fisheries within ecologically meaningful boundaries which seeks to manage the use of natural resources, taking account of fishing and other human activities, while preserving both the biological wealth and the biological processes necessary to safeguard the composition, structure and functioning of the habitats of the ecosystem affected, by taking into account the knowledge and uncertainties regarding biotic, abiotic and human components of ecosystems” (E.U., 2013).

2. Implementation in the European Union

Few explicit objectives for biodiversity exist, mainly focusing on the protection of rare and vulnerable species and habitats (Greenstreet, 2008; Rochet *et al.*, 2011). At the EU level, the main basis for an EAF is provided in the objectives of the Marine Strategy Framework Directive (MSFD) and the CFP.

i. The Marine Strategy Framework Directive (MSFD)

The MSFD focuses on the implementation of an ecosystem approach to the management of human activities taking place in the marine environment, and aims at achieving Good Environmental Status (GES) for European waters by 2020 (E.C., 2008a; Ramírez-Monsalve *et al.*, 2016). The MSFD has introduced eleven qualitative descriptors which describe what the environment would look like after achieving GES. Some of these descriptors represent the ecosystem features of concern. Regarding the effect of fisheries, the descriptors of interest are biodiversity (D1), non-indigenous species (D2), commercial fish species (D3), food webs (D4) and sea floor (D6) (E.C., 2008; Berg *et al.*, 2015). The other descriptors represent human drivers that put pressures on the ecosystem, including fishing activities contained within the previously mentioned D3 (E.C., 2008; Berg *et al.*, 2015).

ii. The Common Fishery Policy (CFP)

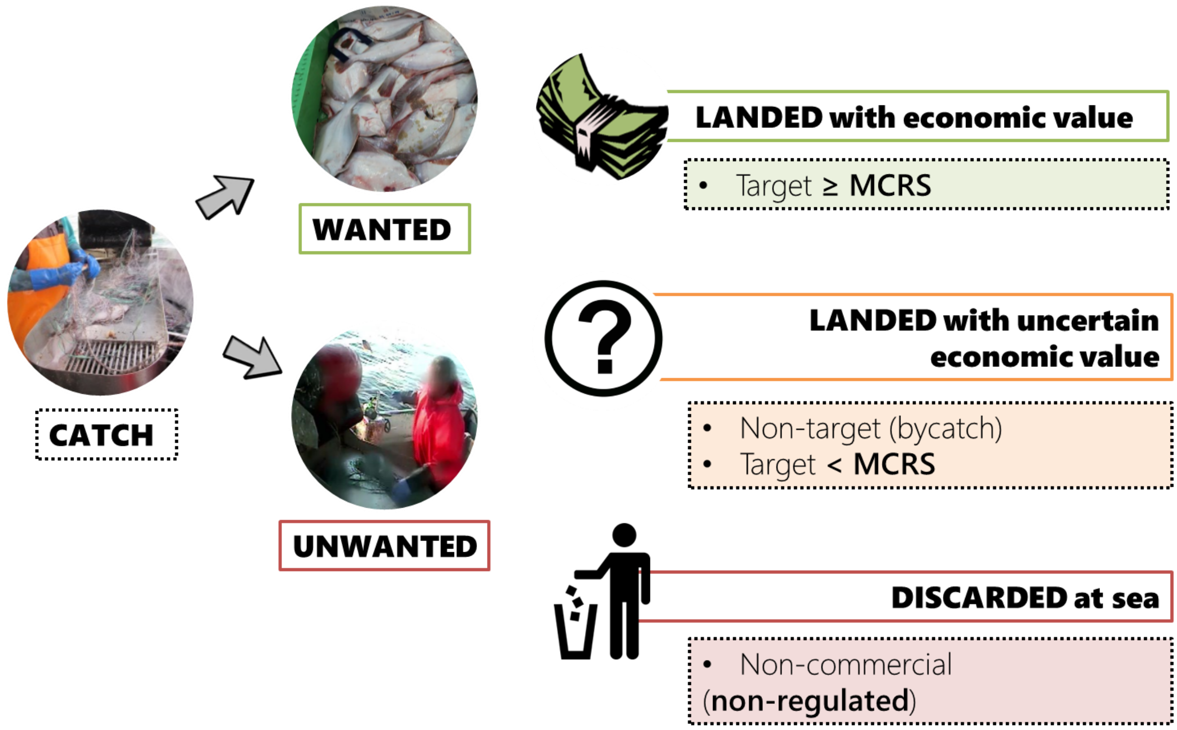
The CFP focuses on the implementation of an ecosystem approach to the management of fisheries activities (Ramírez-Monsalve *et al.*, 2016). For example, the 2013 reform has brought in multiannual plans including several stocks if exploited together. Besides, the new CFP has introduced an obligation to land species subject to catch limits, i.e., managed through Total Allowable Catches (TAC) and quotas (E.U., 2013). A Minimum Conservation Reference Size (MCRS) was established for those species, based on the previous legal Minimum Landing Size (MLS), below which the sale of catches is restricted to non-human consumption products such as fish meal or pet food (E.U., 2013) (*Fig. 1*). Previously, catches below MLS, with insufficient quota, poor condition and limited or no market could deliberately be thrown at sea. Bycatch and discards have, to some extent, similar ecological consequences to the target part of the catch, but, as they do not hold any economic benefit to fishers, represent additional unnecessary mortality (Bellido *et al.*, 2011). The landing obligation aims at encouraging more selective fishing practices in order to reduce bycatch and discards, which have been identified as a threat to the ecosystem's structure and functioning (E.U., 2013).

iii. Current status

Regarding the MSFD, EU countries reported in 2012 their initial assessment, definition of GES and determination of targets and indicators. Each EU country assessed the environmental status of its marine waters, and developed a monitoring programme of measures to reach or maintain GES by 2020. The marine strategies are to be reviewed every six years.

The landing obligation has been gradually implemented since January 2015 fisheries by fisheries (E.U., 2013). Plan for each group of fisheries and area are being established based on joint recommendations from regional groups of member states, and evaluated by the Scientific, Technical and Economic Committee for Fisheries (STECF) of the European Commission (EC). Discard plans last 3 years, and will eventually be incorporated into the previously mentioned multiannual plans. The landing obligation entered into force for demersal fisheries in the North Sea (ICES area IV), Skagerrak and Kattegat (ICES area IIIa) in January 2017 (E.U., 2016). All catches of cod, haddock, sole, whiting, Northern prawn and Norway lobster caught by gillnets and trammel nets are therefore to be landed.

Figure 1. Fate of catch under the landing obligation.



3. Gear technical contributions

The implementation of the EAF in EU entails a limitation in environmental impacts of fishing activities. The combination of gear technical characteristics, i.e., gear design and operational tactics, and conditions of the fishing operation, e.g., meteorological conditions, determine the species and size composition of the catch, as well as the gear dynamic behavior and therefore its potential habitat damage. Gear technological considerations are therefore necessary to better understand ecosystem effects of fishing, and to fully implement an EAF.

Scientific advice in an ecosystem context may lead to short-term economic costs before achieving long-term ecological, social and economic benefits (Jennings and Revill, 2007). The solutions suggested usually involve stopping fishing in sensitive areas and periods (Kennelly and Broadhurst, 2002). However, gear technologists can play a central role in searching for win-win solutions so that fishing can continue in an ecologically sustainable manner (Kennelly and Broadhurst, 2002; Jennings and Revill, 2007).

B. The Danish bottom-set net fisheries

1. General description

i. The fleet

Gillnets stand as the fourth most important general gear type (out of 8) contributing to the global marine catches in weight (based on data from 1950 to 2001, Watson *et al.*, 2006). In 2016, there were 733 registered vessels for bottom set nets in the Danish fleet, among which 69%, i.e., 506 vessels, were professional (NaturErhvervstyrelsens, 2017a). In 2016, about 30% of the registered professional Danish vessels belonged to the bottom set nets fleet (NaturErhvervstyrelsens, 2017). The bottom set netters participate in the mixed human consumption demersal fisheries harvesting round and flatfish in the North Sea, Skagerrak and Kattegat (Vestergaard *et al.*, 2003; Andersen *et al.*, 2012). Although the fleet has reduced in number since the mid-1990s (*Fig. 2*, based on vessel registered in the EU fleet register database, including those with fishing as a subsidiary activity), by landing annually about 7720 t (*Fig. 3)*, the Danish bottom set netters still contribute on average to 17% of the total annual Danish landings of flat and round fish for human consumption (2011-2015, landings data from the AgriFish Agency, processed by DTU Aqua) (NaturErhvervstyrelsens, 2017b).

Figure 2. Number of vessels registered with gillnet or trammel net as main gear in the EU fleet register database, i.e., including those with fishing as a subsidiary activity (E.C., 2016) by year and length class.

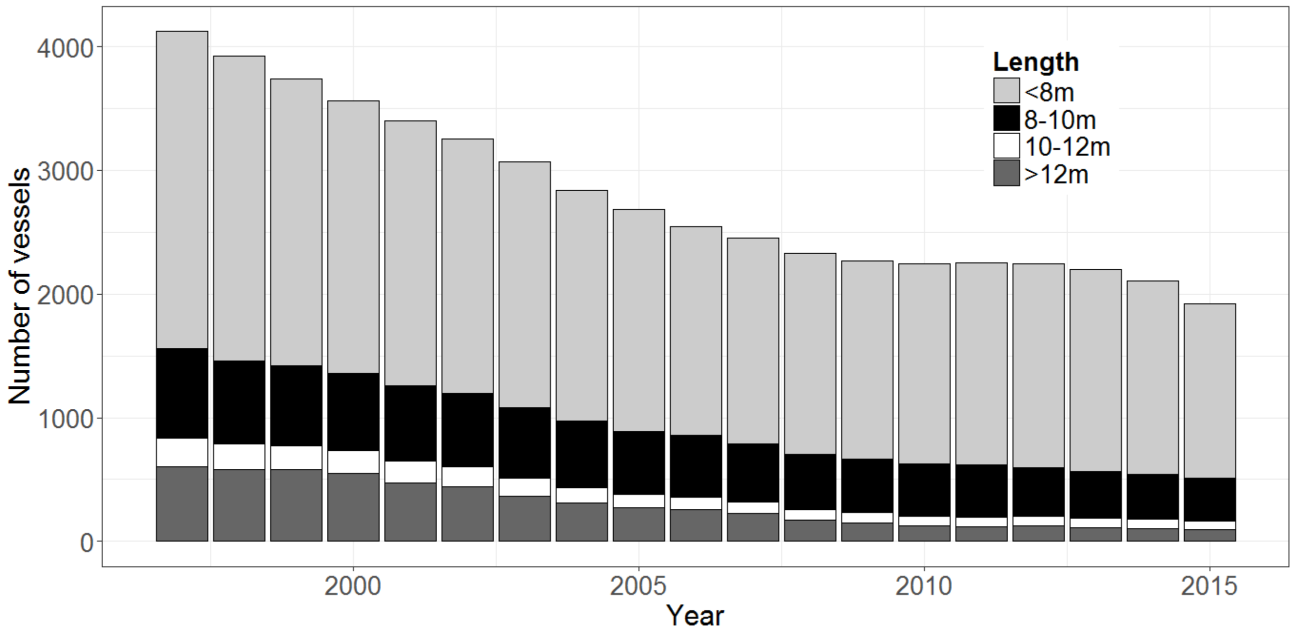
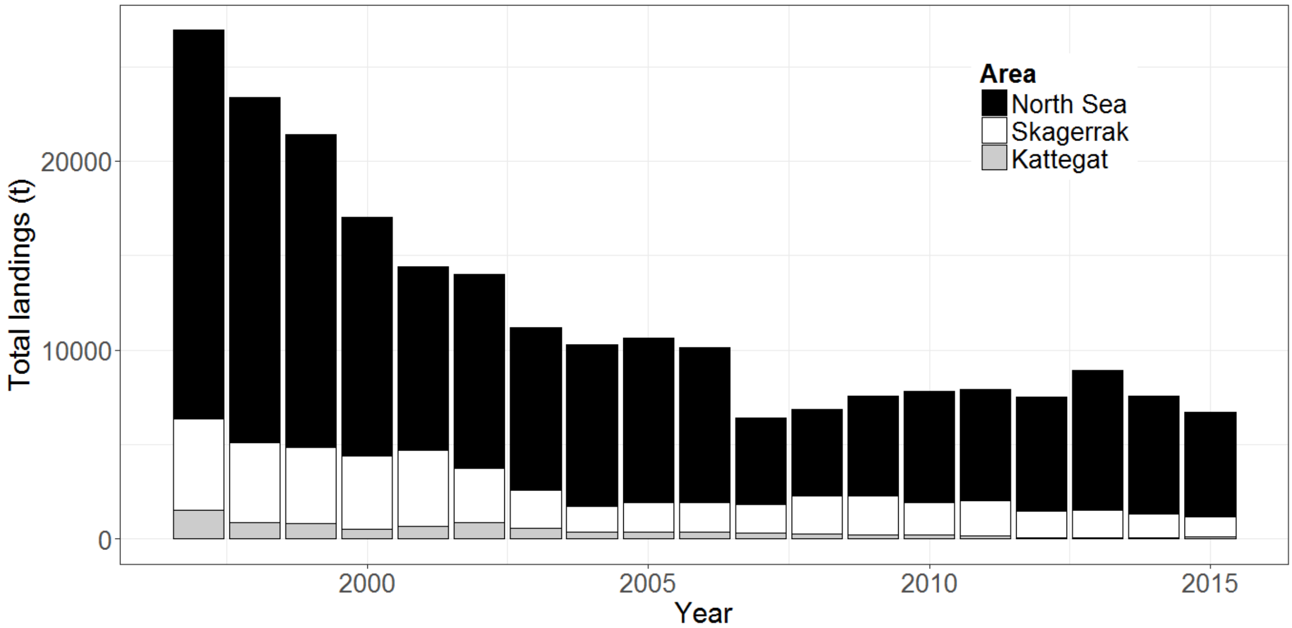


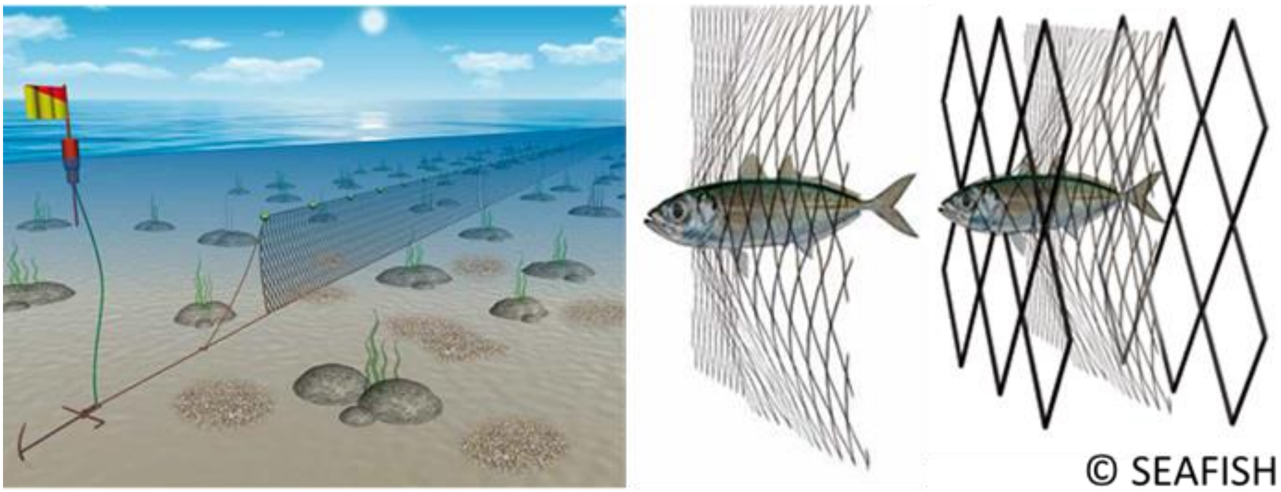
Figure 3. Total landings in tons by the Danish bottom set netters for the North Sea, Skagerrak and Kattegat (landings data from the AgriFish Agency, processed by DTU Aqua).



ii. The gear

Bottom-set nets are designed to stand at the bottom for targeting demersal species such as cod or flatfish (Hovgård and Lasse, 2000). A typical gillnet consists of webbing attached at intervals to the headline and the leadline (He and Pol, 2010) (*Fig. 4*). The net is spread vertically by the buoyancy of floats on the headline and weight in the leadline (Hovgård and Lasse, 2000; Takagi *et al.*, 2007; He and Pol, 2010). The choice of headline buoyancy depends on the target species, but also on the environmental fishing conditions: less buoyancy is required in the Baltic than in the North Sea for example, due to the absence of strong tidal currents.

Figure 4. Bottom set nets (left), gillnet (middle) and trammel net catching method (right).



iii. *Difference between gill and trammel nets*

A gillnet consists of a single netting wall, whereas a trammel net consists of three layers of netting: a slack middle net with a smaller mesh size, and two outer nets with larger mesh sizes (Hovgård and Lassen, 2000; He and Pol, 2010) (*Fig. 4*). The dominant method of capture in gillnet is by gilling, i.e., when a fish is retained by its gills in the net, but individuals can also be caught by the largest part of the body, by the mouth or head region, or by spine and fins as a result of struggling (He and Pol, 2010). The dominant method of capture in trammel nets is by entangling, i.e., when whole or part of the body of the fish is entangled in the pocket of the smaller mesh net (*Fig. 4*). In both gear types, the capture process is based on the fact that the fish does not see the netting and actively swims into the gear.

In the Danish fleet, 3% on average of the vessels with gillnet as main gear also declared using trammel nets as second gear (1997-2015, based on vessel registered in the EU fleet register database, including those with fishing as a subsidiary activity) (E.C., 2016).

2. Fishing operation (FO)

i. Deployment of a fleet on the bottom

Several nets are usually attached together to form a fleet. The fleet is set on the bottom (*Fig. 5*), and usually moored at both ends with weights or anchors (He and Pol, 2010). Nets are anchored to the bottom using 4 to 8 kg anchors on average, ranging from 1 to 2 kg for smaller vessels to up to 14 kg for bigger vessels. In Denmark, fleets are commonly soaked from west to east to avoid gear collision, which is also the main wind – and current – direction in Danish waters.

ii. Soaking

Nets are soaked for various durations, depending on the target species, but also on the fishing ground or season (*Table 1*). Soak duration can be very short, e.g., around an hour in the cod wreck fishery, up to several days in the monkfish fishery.

iii. Hauling

Nets can be hauled by hand in very small vessels, but the use of net hauler is now very common (*Fig. 5*). The fisher manually untangles the catch from the net (*Fig. 5*). Fishing with nets is therefore known to be labour intensive, and handling of the catch plays an important role in fishing effort and tactics (Suuronen *et al.*, 2012).

3. Danish bottom set nets fleet and fisheries

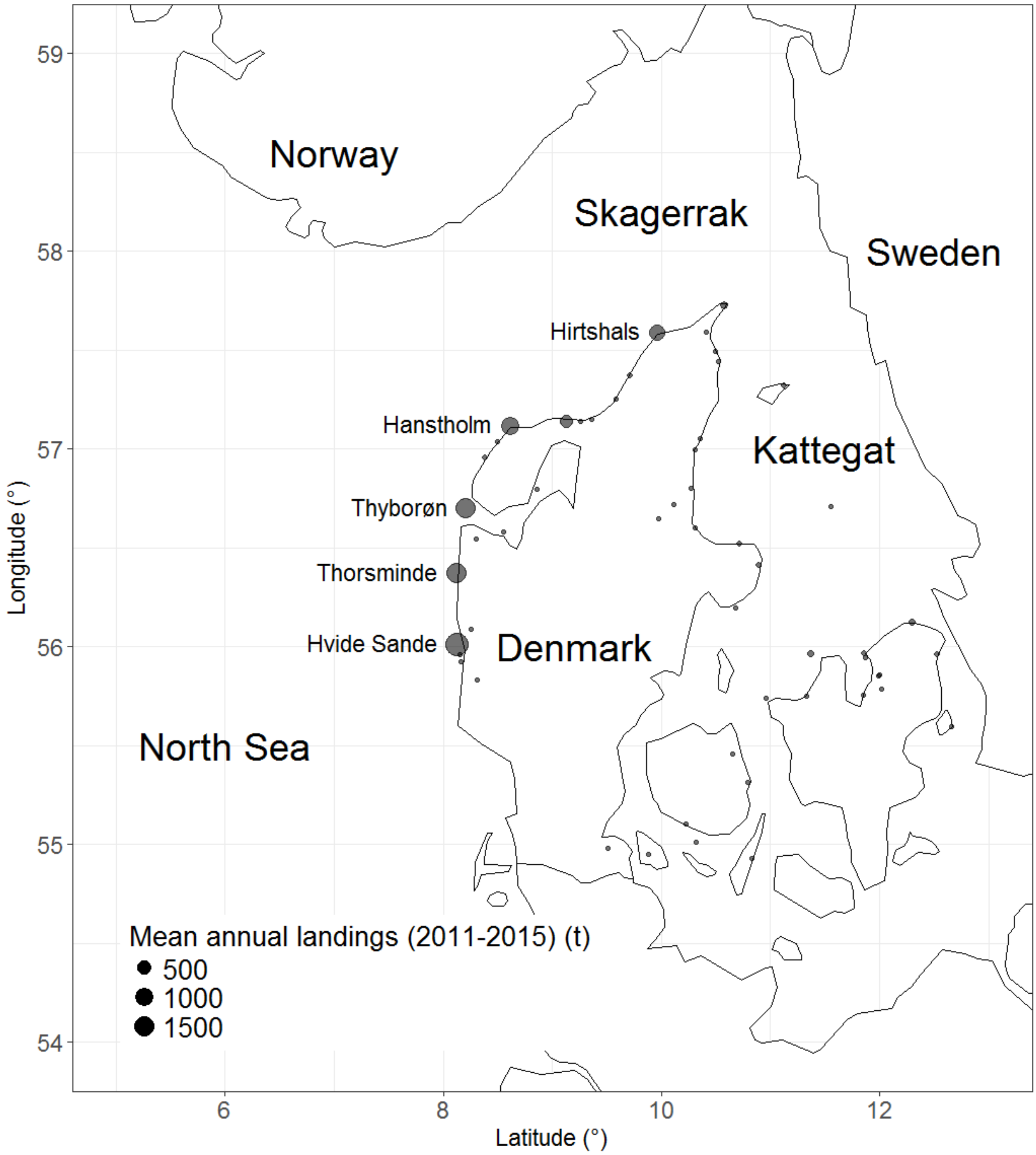
i. Home harbour, fishing area and operational range

Most netters are based in the northern west coast of Jutland, e.g., Hirtshals, Hanstholm and Thyborøn, or in the southern west coast of Jutland, e.g., Thorsminde and Hvide Sande (*Fig. 7*), but

Figure 5. Deployment of a fleet from the back of the vessel (top left), a net fully deployed on the bottom (top right), hauling the fleet with a hauler from the side of the vessel (bottom left) and untangling the catch (bottom right).

Figure 6. Danish netters of different length classes.

Figure 7. Mean annual landings in tons (2011-2015, landings data from the AgriFish Agency, processed by DTU Aqua) by harbours landed by the Danish bottom set netters in Denmark.



some vessels can temporarily change landing harbour for the season of a given fishery (Andersen *et al.*, 2012). Some vessels also land in the Netherlands, Norway and the United Kingdom with on average respectively 512, 129 and 4 tons landed annually (2011-2015, landings data from the AgriFish Agency, processed by DTU Aqua). Most vessels in the Danish bottom set nets fleet participate in the North Sea and Skagerrak fisheries (*Fig. 3*). Most vessels are relatively small (*Fig. 2*) and fish for daily trips in coastal areas.

ii. Target species and seasonality

Bottom set nets tend to be relatively species selective, and often target a single species at a time, changing fishing ground and sometimes gear from one season to the other (Vestergaard *et al.*, 2003; Ulrich and Andersen, 2004; Andersen *et al.*, 2012) (*Table 1*). Danish bottom set nets target a range of bentho-demersal fish (*Table 1*), cod, plaice and sole being the most important ones in weight (*Table 2*). In the context of mixed-species fisheries, there can be a shift in target species driven by the scarcity of the resource, e.g., a switch from cod to plaice was observed in the North Sea (Marchal *et al.*, 2002).

Table 1. Characteristics of the gear and fishing ground of fishing operations sampled by the Danish observers at sea sampling program between 1998 and 2016 in the North Sea, Skagerrak and Kattegat per target species (Target): number of fishing operations (FO) and number of different vessels (Vessel) sampled for gill- (G) and trammel nets (T), quarter (Quarter), range (min-max) of the soak duration in h (Soak), the full mesh size in mm (Mesh size), the total net number (Net nr.), the length of an individual net in m (Net length) and the depth in m (Depth). Information in bold gives the most common occurrence of the different events.

Target	Gear	FO	Vessel	Quarter	Soak	Mesh size	Net nr.	Net length	Depth
North Sea									
Hake	G, T	14	4	3	4-14	125-150	40-200	60	27-83
Turbot	G	22	6	2, 3	2-214	170-270	40-200	70-87	22-75
Plaice	G, T	106	16	**1**, **2**, **3**, 4	2-123	120-180	5-200	50-92	0-56
Lumpfish	G	2	1	2	51-99	220-260	45-85	-	10
Sole	**G**, T	39	6	**2**, 3	9-50	92-124	90-448	47-72	5-42
Cod	**G**, T	490	20	**1**, **2**, **3**, **4**	0-44	130-300	2-240	42-75	8-157
Skagerrak									
Monkfish	T	4	3	3, 4	97-124	250-270	95-200	80-90	55-83
Hake	G	3	2	3, 4	3-17	130	80-220	60-62	50-71
Pollack	G	6	4	1, 2, 4	3-13	120-150	6-260	55-60	19-104
Plaice	G, T	31	11	2, 3, 4	2-48	70-200	10-240	50-100	7-47
Lemon sole	G	2	1	3, 4	24	150	80-120	-	35-50
Sole	**G**, T	8	3	2	6-25	96-124	60-144	45-56	8-19
Cod	G, T	80	14	**1**, **2**, 3, **4**	2-73	115-180	2-218	45-100	10-105
Kattegat									
Turbot	G	1	1	2	64	240	12	62	5
Plaice	T	2	2	3	20-27	120-140	36-90	55	16
Lemon sole	T	1	1	3	18	130	48	50	18
Lumpfish	**G**, T	27	5	1, 2	46-312	120-270	12-100	62-85	18
Sole	G, T	45	13	1, **2**, 3, **4**	5-72	92-150	9-600	45-88	18
Cod	T	10	4	1, 2, 3, 4	10-44	120-130	36-64	50-53	22

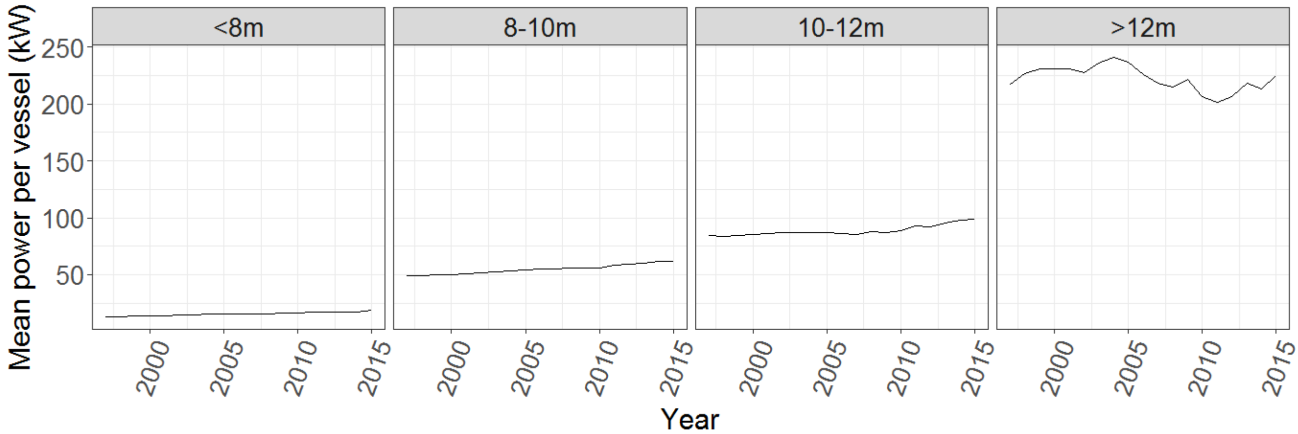
Table 2. Mean annual landings (2011-2015, landings data from the AgriFish Agency, processed by DTU Aqua) by bottom set nets for the first five main species landed in the North Sea, Skagerrak and Kattegat.

North Sea		***Skagerrak***		***Kattegat***	
Species	Annual landings (t)	Species	Annual landings (t)	Species	Annual landings (t)
Plaice	3078	Cod	648	Lumpfish	34
Cod	1477	Plaice	405	Sole	19
Sole	351	Pollack	110	Plaice	12
Hake	339	Monkfish	56	Herring	6
Turbot	283	Saithe	25	Pollack	5

iii. Vessel length, horsepower, tonnage and crew size

Vessel length, horsepower and tonnage are not very good descriptors of effective capacity in fisheries with static gears. Except for few specific fisheries that require bigger vessels, either to handle high nets (6 m), e.g., for saithe and hake, or to allow for a larger and more powerful hauler to fish offshore in deeper waters, e.g., for saithe and monkfish, there is no additional gain in fishing power for bigger vessels that can operate more nets due to the necessity of manually handling the catch. This is reflected in the Danish bottom set net fleet structure where small vessels are still predominant compared to the trawl fleet (*Fig. 2, Fig. 6*) and where the increase in power per vessel has remained relatively stable throughout the years (*Fig. 8*).

Figure 8. Mean power per vessel in kW for Danish vessels registered with gillnet as main gear in the EU fleet register database, i.e., including those with fishing as a subsidiary activity (E.C., 2016) by length class and year.



Most of the very small vessels, i.e., length class less than 8m, are however mostly fishing as a subsidiary activity (*Fig. 2*). If bigger vessels permit the same handling amount per crew member per hour, one has to note that they still provide with the possibility of more days at sea by being able to fish in rough weather, a larger crew and a higher number of nets. The latter can be useful to have different nets for different target species, or as in the sole fishery for example, to be able to let the unwanted dab and plaice rot while fishing with other nets to skip the handling labour.

Usually the vessel is owned by a single man, with one or two crew members, but vessels participating in labour demanding fisheries, e.g., the sole fishery along the Dutch coast, can have larger crews.

iv. Access to and management of the fisheries

Access to the Danish fisheries requires both recognition as a commercial fisherman and a vessel license. Before 2007, the seasonal allocation of the Danish quota for most demersal stocks was through a catch-ration system, the ration size depending on the vessel size for a given stock, but not the gear type (Andersen *et al.*, 2012; Vestergaard *et al.*, 2003). In 2007, Individual Transferable vessel Quotas (ITQ) were implemented in the Danish demersal fishery (Andersen *et al.*, 2012). Few technical regulations apply to bottom set nets in the European waters, except for the hake and monkfish fisheries which are restricted in mesh size, number of nets and soak time (COM, 2016). However, fishermen are restrained in their fishing effort by workload. Disentangling catch from the netting can be time consuming, and as netters usually operate on vessels less than 12m with limited crew, handling time is a major limiting factor for additional fishing power.

4. Gear characteristics

i. Hanging ratio

The hanging ratio measures how tightly the netting is stretched along the headline and the leadline, modifying slackness of the netting (Hovgård and Lassen, 2000; He and Pol, 2010). The hanging ratio vary between 0 with all meshes mounted at the same point on the ropes so the net has no length dimension and 1 with the netting fully stretched out so the net has no height dimension (Hovgård and Lassen, 2000). Hanging ratios are found between 0.25 and 0.65 in commercial fisheries, with lower hanging ratios for flatfish and higher ones for roundfish (Wileman *et al.*, 1999; Hovgård and Lassen, 2000; He and Pol, 2010).

ii. Netting material and colour

The netting can be made of monofilament, multimonofilament or multifilament. Monofilament nets consist of monofile nylon thread, which can also be combined in multimonofilament, whereas multifilament are thin nylon fibres twisted together. The netting material, numbers of filaments in the twine, and twine size affect the visibility of the netting and the mechanism of fish capture (He and Pol, 2010). Nets constructed of thinner twine were found to catch more fish than those made of thicker materials, as they are less visible and softer (Hovgård and Lassen, 2000; He and Pol, 2010). However, thinner twines may also have a poorer size selection due to the netting elongation when a fish pushes into the mesh and a higher tendency for entangling, including invertebrates (Hovgård and Lassen, 2000; He and Pol, 2010). They are also more easily damaged, which may result in increased costs and lost fishing time (Hovgård and Lassen, 2000; He and Pol, 2010). Therefore, choice of netting material and twine thickness implies a trade-off between fishing power and net durability, depending on the type of fisheries. For example, multifilament may provide with strength not required for coastal fisheries.

The most efficient colour, which makes the netting invisible to the fish, depends on the target species, water and seabed colours, and twine thickness (Hovgård and Lassen, 2000). A general trend was observed with preference for grey or green in the North Sea (Hovgård and Lassen, 2000).

iii. Mesh size

Mesh size is likely the most important factor affecting size selectivity (He and Pol, 2010). Thus, mesh size vary with the target species, e.g., small mesh size of less than 120 mm (full mesh) for sole, and more than 220mm for turbot (*Table 1*). Mesh size can also vary throughout the year for the same target species, e.g., larger mesh sizes are used in spring (140-150mm, full mesh) compared to winter (120-130mm) in the Bornholm cod fishery as cod is full of roe.

iv. *Net dimensions*

Net height depends on the target species and fish behavior. Nets are high in the hake (5-6m) or cod wreck (3-5m) fisheries. Lower nets are more likely to tangle up.

Individual nets of a limited length can be used, e.g., 3 nets of about 45 m set in parallel in the cod wreck fishery, or a total net length as long as 100 km such as in the turbot fishery, but about 30 km of nets are usually soaked in a typical bottom-set gillnets fishing operation (Montgomerie, 2015) (*Table 1*). The total net length partly depends on the man power onboard the vessel, e.g., 2.5 to 6 km for a single crew vessel.

C. Challenges for an Ecosystem approach to the Danish bottom set nets fisheries

1. Main potential fishing effects on the ecosystem

i. Selectivity of target and non-target species

Selective fishing is the ability of a fishing gear to target specific types of individuals, allowing unwanted sizes and species to avoid capture (Wileman *et al.*, 1996; Breen *et al.*, 2016). Gillnets are, in general, considered as being size selective, with larger mesh sizes catching larger fish (Stergiou and Erzini, 2002; He and Pol, 2010). Retention of fish in gillnets increases with fish size up to a length of maximum catch and decreases afterward (Millar and Fryer, 1999; Fonseca *et al.*, 2002; Fauconnet and Rochet, 2016). However, all species are not equally vulnerable to the gear, and nets can catch various species (Fonseca *et al.*, 2002; Valdemarsen and Suuronen, 2003; He and Pol, 2010; Breen *et al.*, 2016). Compared to gillnets, the selectivity of trammel nets are lower due to the higher variety of capture mechanisms, i.e., gilling, wedging, entangling and pocketing, associated with trammel nets

(Borges *et al.*, 2001; Erzini *et al.*, 2006; Gonçalves *et al.*, 2007; Batista *et al.*, 2009). There is therefore an interest in reducing bycatches of undersized target species and non-target species. As part of the EAF approach, selective fishing is encouraged to reduce bycatch and discards, but there is an important scientific debate regarding whether selective fishing on adult age classes of few commercial species is ecologically preferable than distributing a moderate fishing mortality across the widest possible range of species, stocks and sizes, the latter being known as balanced harvesting (Zhou *et al.*, 2010; Rochet *et al.*, 2011; Garcia *et al.*, 2012; Breen *et al.*, 2016; Ulrich *et al.*, 2016). A conservation perspective can also aim at the trophic level balance of the ecosystem, i.e., removing low and high trophic level classes in percentages higher and lower, respectively, than those found in the ecosystem (Stergiou *et al.*, 2007).

Incidental catch of a number of vulnerable species such as skate and rays, turtles, marine mammals or seabirds, is a matter of growing concern in certain areas, e.g., bycatch of harbour purpoise in the lumpfish fishery in Denmark. Previous research projects focused on the catch of marine mammals in the bottom set nets fisheries for cod in the Baltic Sea (Kindt-Larsen, 2015).

Ghost fishing, i.e., when lost nets continue fishing, is also a serious issue worldwide, but of less concern in shallow areas such as those fished by the Danish netters as lost nets are commonly rapidly rolled up by storm and tide action (Brown and Macfadyen, 2007).

ii. Genetics of exploited populations

Catching fish above a minimum size increases the relative mortality of fast-growing individuals and favours early maturity and slow growth. In set net fisheries, the selectivity curves are already (double) dome-shaped and may encourage favourable genetic selection (Jennings and Revill, 2007).

iii. Food webs

Fishing affects the predator-prey interactions, including predators of conservation interest such as seabirds and mammals. In most fisheries, the understanding of fishing effects on food webs is not sufficient to assess how changes in gear technology might mitigate any unwanted food web effects (Jennings and Revill, 2007). However, gear technology can contribute to better understand the capture pattern of bottom set nets, which are likely to have an effect on food webs, e.g., by discarding at sea unwanted catches not regulated by the landing obligation.

iv. Habitats

Habitat damage is of high interest in an EAF as some fishing gears can remove or damage habitat forming structures, potentially reducing the complexity, diversity and productivity of benthic environments (Jennings and Kaiser, 1998; Kaiser *et al.*, 2000; Kaiser *et al.*, 2002; Hermsen *et al.*, 2003; Grabowski *et al.*, 2014). It is generally assumed that habitat impacts of passive gears are lower than those of active gears, and most likely during retrieval of the gear only (Suuronen *et al.*, 2012;

Grabowski *et al.*, 2014). However, these conclusions are based on few experimental studies. For example, there were only five studies regarding passive gears, i.e., longlines, traps and gillnets, out of 97 used for the latest assessment in New England, US (Grabowski *et al.*, 2014). There is no direct evidence of potential effect for many of the current habitat-gear combinations (Eno *et al.*, 2013). Taking a closer look at bottom gillnets, the lack of studies regarding habitat impact might be attributed to the general assumption of negligible effects (Uhlmann and Broadhurst, 2013). However, after in situ observation at two rocky reefs, Shester and Micheli (2011) identified set gillnets as a priority conservation concern due to their potential to damage habitat-forming species. In the Welsh part of the Irish Sea, Eno *et al.* (2013) assessed nets sensitivity as high to medium for high to low fishing intensities in 8 habitats out of 31, mostly rock with associated branching species such as kelp, seaweeds or maerl beds. The degree to which passive gears drift on the bottom has therefore to be quantified for the different bottom types (Grabowski *et al.*, 2014).

2. Limited information on passive gears

The limited information on passive gears is partly due to historical focus on active gears, but also because data collection and analysis calls for the development of appropriate innovative assessment methodologies to properly assess the new type of information which has to be gathered as part of an EAF. Challenges include (1) the difficulty to find an appropriate quantitative method that can be used in-situ around entangling nets, (2) the need to standardize data before comparing catch from nets of various fishing effort due to the use of different gear types, mesh sizes, net length and/or soak durations, and (3) the prerequisite of having modelling methods and software to properly analyse bottom set net data.

3. Aim of the PhD project

Bottom set nets do not represent the largest number of professional vessels in the Danish fleet, but they account for about 80% of the total number of vessels registered in Danish waters (E.C., 2016) and are passive gears often proposed as a potential alternative to active fishing gears in, e.g., sensitive areas. Bottom set nets have the advantage of low energy consumption, low investment cost and relatively good size selectivity, but they are work intensive and some disadvantages remain, such as poor species selectivity and catch quality, as well as unclear habitat impacts. There is limited knowledge about the ecosystem effects of bottom set nets partly due to historical focus on active gears, but also because data collection and analysis calls for the development of appropriate innovative assessment methodologies. Thus, focus was given to methodological development (Part **II**), catch pattern (Part **III**) and habitat effects (Part **IV**) (*Table 3*).

Table 3. Gear technical parameters looked at for each of the EAF component of focus in the present thesis for different case studies. Each case study included the development or use of an adapted methodology (Method), including Generalized Linear Mixed Model (GLMM), Catch Damage Index (CDi) and Cumulative Linear Mixed Model (CLMM). The corresponding part in the synopsis is given, together with the resultant paper.

		Catch pattern			**Seabed effect**
		Catch pattern	Discard ratio	Catch quality	Seabed effect
Gear technical parameter		Soak	Fishery, soak, depth	Soak	Light/heavy nets
Case study	Gear	Gillnet	Gill- trammel	Gillnet	Gillnet
	Target	Plaice	Cod, plaice, sole	Plaice	Plaice
	Ground (coastal)	Skagerrak	North Sea	Skagerrak	Skagerrak
	Season	Summer	All year	Summer	-
	Data	Experimental	Commercial	Experimental	Experimental
Method		Catch comparison	Discard ratio, betaGLMM	CDi, CLMM	Stereo imaging
Synopsis		II, III-1	II, III-2	II, III-3	II, VI
Paper		Paper **I**	Paper **II**	Paper **III**	Paper **IV**

Even if the exact ecosystem effects are not known, there is an overall interest in reducing bycatches of undersized target species and non-target species. Focus was given to the fish species regulated by the new landing obligation (Paper **II**), but also to the overall species composition (Part III) and one of the most important fish species targeted in the Danish fisheries, plaice (Papers **I** and **III**). Regarding catch pattern, one can intend to minimize the catch that is unwanted (Papers **I** and **II**), or to maximize the part of the catch that is wanted (Paper **I**), e.g., by improving catch quality of the target species (Paper **III**). Regarding habitat effect, focus was given to the estimation of the extent of physical damage by bottom set nets, including the development of an assessment method (Paper **IV**).

Gear technological considerations, i.e., **gear design and operational tactics**, can help to implement an Ecosystem Approach to the Danish bottom set nets fisheries (*Table 4*). The selection properties of nets may be improved to limit bycatch (mesh size, netting material, twine thickness), but due to the nature of the gear, one would most likely also impair the catch rate of the target species. New selective technologies involving more complex gear are limited in passive fisheries, and therefore, in many cases, the fisher's operational tactic plays a preponderant role (Kennelly and Broadhurst, 2002; Andersen *et al.*, 2012; Eliasen *et al.*, 2014; Fauconnet *et al.*, 2015; Breen *et al.*, 2016; Fauconnet and Rochet, 2016). It has the advantage of no additional economic cost, workload or risk (Sigurðardóttir *et al.*, 2015). The effects of gear design, i.e., light and heavy nets, on habitat effects (Paper **IV**) and fisher's tactic, i.e., soak duration or choice of target species, on catch pattern and quality (Papers **I**, **II** and **III**) were explored (*Table 3*).

Table 4. Contribution of fishing gear technology to the EAF in the bottom set nets fisheries.

GEAR design & OPERATIONAL tactics determine:	Objectives in an ECOSYSTEM APPROACH:
✓ Species and size composition of the catch	✓ Limit unwanted catch
✓ Gear dynamic behaviour	✓ Limit seabed effects

Change in gear design and operational tactics aiming at a better environmental sustainability should of course also guarantee socio-economic sustainability and help maximize fisherman profit. The best soak tactic in the fisher's interest was assessed in Papers **I** and **III**. In the new landing obligation system, all catch of regulated species are to occupy space in the vessel's hold and be deduced from the vessel's quotas. The discard ratio of regulated species was therefore used as a proxy for the non-profitable fraction of the landed catch to assess if the landing obligation would have an economic impact on fishers (Paper **II**).

- ✓ Bottom set nets are one of the most widely used fishing gears, but there is limited knowledge about their ecosystem effects.
- ✓ Bottom set nets have the advantage of low energy consumption and good size selectivity. However, some disadvantages remain, such as poor species selectivity and catch quality, as well as unclear habitat impacts.

II. MATERIAL AND METHODS

A. Find an appropriate quantitative method

1. Experimental set-up: stereo-imaging

Several optical or acoustic techniques have been developed as complementary tools to assess the impact of active gears on the seabed (Smith *et al.*, 2003; Humborstad *et al.*, 2004; O'Neill *et al.*, 2009; Lucchetti and Sala, 2012; Depestele *et al.*, 2016). However, not all techniques provide a spatial resolution fine enough to assess the effects of bottom set nets. Others are restrictive in sampling duration. Underwater videos appear as an appealing candidate, with cost efficiency, high precision and less bias than direct visual observation, but their use as informative data also depends on the ability to extract relevant measurements (Struthers *et al.*, 2015; Neuswanger *et al.*, 2016). Eventually, not all techniques can easily and safely be run around bottom set nets, prone to entanglement. We tested for a method to quantitatively assess the dynamic behavior of the leadline of the nets.

i. Experimental set-up

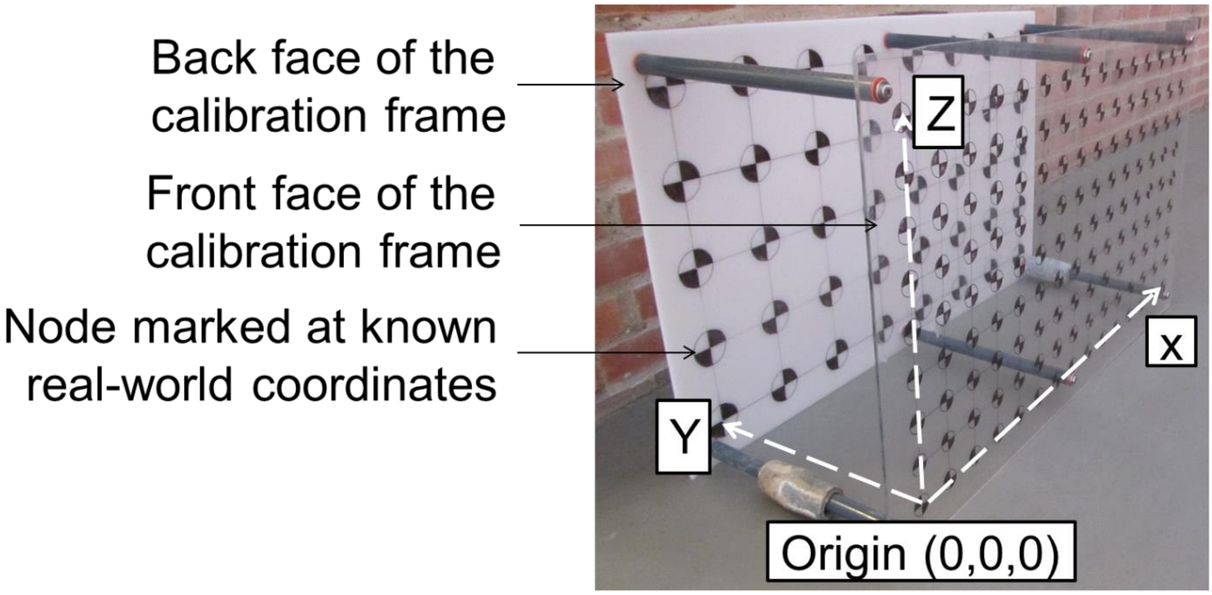
Stereo imaging consists in two cameras taking synchronized images of a scene from slightly different perspectives, which then allow to estimate the distance to an object such as in the human 3D vision. A stereo imaging method, currently used in other fields, e.g., to count fish underwater (Graham *et al.*, 2004) was identified and adapted. A stereo recording unit, composed of a metallic frame on which were attached two cameras, was positioned on the seabed facing the middle length of a fleet (**Paper I**).

ii. Data collection and analysis

If an object is uniquely identified in both images and if the translation and rotation of one camera relative to the second is known, it is then possible to estimate the location of the object in 3D space (Schmidt and Rzhanov, 2012). Nets were marked with different red tape patterns on the leadline to make sure that these marks would easily be uniquely identified. The video clips were processed with the free open-source Mac application VidSync version 1.66 (www.vidsync.org), based on the OpenCV library computer vision algorithms (Neuswanger *et al.*, 2016).

Before the proper calculation of the 3D coordinates of a point, one has to correct for lens distortion and establish the perspective of each camera. Lens distortion is induced by the fisheye lens of the camera, meant to widen its angle of view, but particularly pronounced when the camera records underwater through housing and prone to bias calculations. Correction factors, or distortion parameters, can be found by locating nodes on a chessboard pattern and arranging them into straight lines (*Fig. 9 and 10*). The same chessboard pattern can be used to calculate the projection matrices for each camera by matching the known physical 2D node coordinates on each face of the calibration frame with screen coordinates, which were recorded in VidSync by clicking on the centre of each node on the clips (*Fig. 10*). The position of the calibration frame defined the 3D coordinate system (*Fig. 9*).

Figure 9. 3D calibration frame – partly reproduced from *Savina, E., Krag, L.A., Madsen, N. Developing and testing a computer vision method to quantify 3D movements of bottom-set gillnets on the seabed. ICES Journal of Marine Research, 2017, fsx194, https://doi.org/10.1093/icesjms/fsx194* .



The 3D coordinates of a point were calculated in VidSync by iterative triangulation, aiming at establishing two lines-of-sight that approximately intersect at the point of interest. Screen coordinates are projected onto the two planes in real-world space. The 3D position of the mark is the intersection of the line of sight of both cameras. It consisted in clicking on the point of interest, here different points of the leadline, on each clip.

iii. Limitations and further improvement

The adaptation of stereo-imaging to passive fishing gears proved to be a relevant methodology for quantifying gear dynamic behavior in-situ. The following improvements could, however, be suggested.

The stereo-imaging experimental set-up, i.e., the choice of camera separation and the dimensions and position of the calibration frame, was configured to measure relatively small objects close to the cameras. Accuracy and precision decreased as distance from the cameras increased. The nets were not expected to move in such an order of magnitude, but a larger chessboard, i.e., large enough to fill the screen, could have helped limit the measurement errors. The fish eye effect could be reduced by limiting the field of view.

A variety of challenges were faced when deploying the recording units near the nets at sea, among which water turbidity, also noticed as a limitation for optical methods by Lucchetti and Sala (2012) and Struthers *et al.* (2015) (*Fig. 11*). The ongoing adaptation of a time-of-flight camera to work as range-gated camera, i.e., the camera only capture light reflected from objects further away than a certain distance which can be used to remove the effects of scattered light, as part of the Horizon 2020 programme (http://www.utofia.eu/) could solve the issue of water turbidity. The nets got tangled in the cage (*Fig. 11*), leading to a modification of the distance between each camera on the frame as well as the inclusion of a netting protection (**Paper I**). However, the recording unit should be positioned from above, i.e., hanging from the sea surface, provided that measurements are independent of wave activity.

Calibration and distortion corrections obtained in a tank with the same camera specifications for each recording unit as those at sea were used, but any optical adjustment such as removing a camera from its underwater housing to change a battery or a change of the angle between the cameras during transportation/aboard the vessel may have affected the parameters and therefore the results. Control tests did not show major issues with the data, and the order of magnitude of the results can therefore be relied on, but the cameras should remain fixed throughout the experiment.

2. Onboard observations under commercial conditions: CCTV

In addition to experimental set-up, it is also possible to collect data directly onboard commercial vessels, either with Closed Circuit TV (CCTV), or with onboard observers. We explored the potential of CCTV and onboard observers for documentation of catch pattern, including discards.

i. The data set

The dataset was gathered by DTU-Aqua as part of field trial tests (Dalskov and Kindt-Larsen, 2009; Kindt-Larsen and Dalskov, 2010; Kindt-Larsen *et al.*, 2012). It included 14 gillnetters targeting cod and plaice in the Danish waters (North Sea, Skagerrak, Øresund, Storebælt, around Æro/Langeland). The settings (frame rate and lens resolution) and location of the camera(s) aimed at recording marine mammals and birds, as well as cod for some of the vessels, while limiting the use of space on the hard disk in order to have a longer recording duration.

ii. Data analysis

The assessment possibilities of the recordings regarding species discrimination were tested. It was sometimes possible to spot flora such as seaweed. However, flora came most of the time mixed with other species, it was not possible to quantify, and it was not possible to know whether it was torn form the seabed or simply collected as floating flora during the hauling process. Depending on the position of the camera and the picture quality, it was sometimes possible to discriminate invertebrates to the suborder (e.g. crustacean), class (e.g. starfish) or infraorder (e.g. crab) level but

Figure 10. Undistortion and rectification of the stereo images using VidSync - adapted from Bradski and Kaehler (2008).

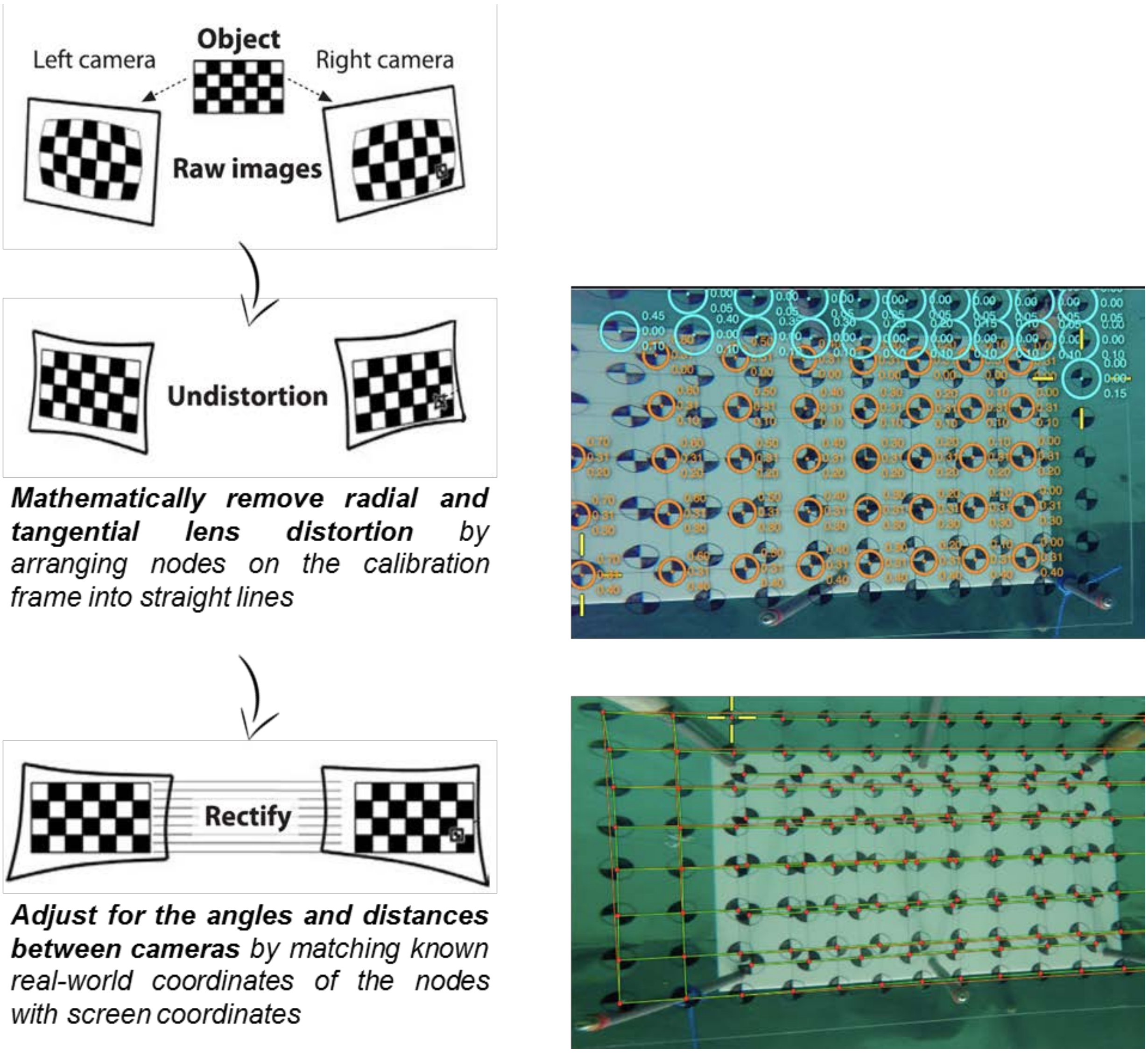


Figure 11. Low visibility (left) and entanglement with the netting (right).

not to the species level. It was sometimes possible to discriminate fish to the species level, or whether it was a round or a flat fish (*Fig. 12*). None of the recordings was suitable for discrimination of all individuals at species level.

The potential use of CCTV for quantifying drop-out, survival/mortality rate, and discard ratio, eventually in relation to fish quality, was assessed. It should have been possible to see individuals falling from the net when hauling, i.e., drop out, on the side camera, but it did not happen in our analysis of the recordings. It was sometimes possible to see if the fish was still moving on the sorting table or, after sorting, in the box on the deck. Depending on the position of the camera and the arrangement of the deck, it was sometimes possible to follow the fate of the catch – kept on board and thrown in a box on deck, or discarded and thrown back to water, or smashed (*Fig. 13*). However, this was not possible on vessels which have one side camera only. None of the recordings was good enough to assess fish quality.

Biological information is also important when looking at gear selectivity. It was sometimes possible to get an idea of the relative length of the individual, in relation to the fisherman size or to the surrounding vessel objects, or in comparison with other caught individuals. However, accurate length measurements were not possible and other biological information such as weight or sex were not available (Dalskov and Kindt-Larsen, 2009). None of the vessel provided with enough data quality for an accurate analysis.

iii. Limitations and further improvement

The number and position of cameras, as well as frame rate and lens resolution, affected the cans and cants of the recordings.

As the trials aimed at evaluating the marine mammals and birds bycatch, it was not necessary to have a complete overview of the vessel activity. Therefore, some vessels only had one camera recording the side of the vessel, whereas others had up to 6 cameras located at various deck locations such as the sorting belt, the boxes where the catch are kept or the hole where discards are thrown. It was obviously easier to get more information with several cameras (*Fig. 14*).

Type and accuracy of the information collected depended on the camera location and how the crew was using the deck. Fishermen might hide the view on the sorting belt if working in front of the camera (*Fig. 15*). An overall view of the deck allowed to spot the fate of catch (discarded or not) but made species discrimination more difficult, contrary to a focus on the sorting belt (*Fig. 15*).

Image quality was highly variable from one vessel to the other, and even sometimes from one FO to the other for the same vessel. Image quality mostly depends on lens resolution and frame rate (Evans and Molony, 2011), but other parameters such as weather conditions or light (day

Figure 12. Starfish (left), cod (middle), unknown round fish (right).

Figure 13. Cod kept (left), flatfish discarded (middle), and crustacean smashed (right).

Figure 14. Four cameras recording side of vessel, sorting belt and sorted catch on deck.

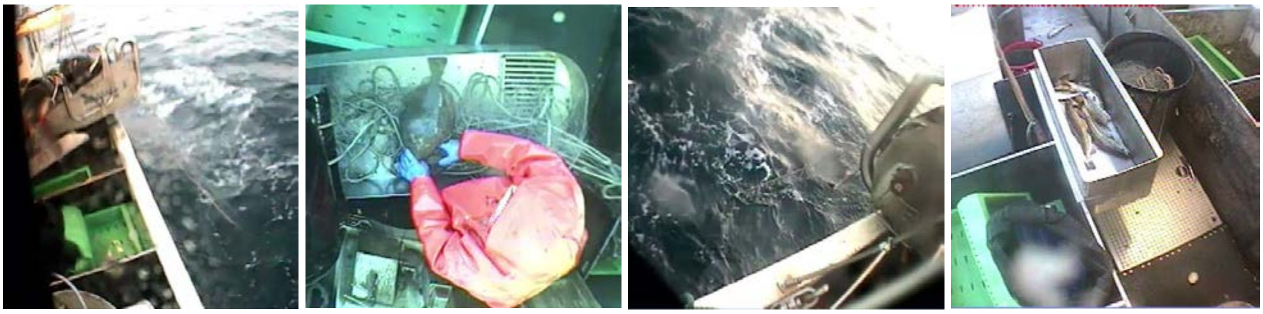


Figure 15. Fisherman hiding view (left), large overview of deck with sorting far from camera (middle), and camera on top of sorting belt (right).

versus night, ray of light) can interfere. The available data did not show enough differences in lens resolution and frame rate to quantify their effects on the image quality.

3. Onboard observations under commercial conditions: observers at sea

i. The dataset

Data was collected on-board commercial fishing vessels by scientific observers during regular FO as part of the national sea sampling programme initially carried out under a national program before 2002 and then under the EU Data Collection Framework (E.C., 2008b). A limited part of the bottom set net fleet is conducting self-sampling, i.e., fishermen are asked to land their discards on randomly chosen days, which are then handled by the observer as a normal discard trip (Storr-Paulsen *et al.*, 2012). Before 2011, observers were responsible for covering a vessel group and area with fixed days at sea, but could choose the vessels. A new stratified random sampling system was introduced in 2011. For each vessel group and area, vessels are weighted with the number of trips conducted in the same area the year before and randomly selected (Storr-Paulsen *et al.*, 2012).

In the Danish sea sampling program, only the top 90% of the métiers ranked by landing amount, landing value or fishing effort are selected for sampling, or if the discard ratio is larger than 5% in weight (Storr-Paulsen *et al.*, 2012). Regarding bottom set nets (gear unspecified, i.e, either gill or trammel nets) in the North Sea, Skagerrak and Kattegat, 7 métiers are currently sampled, all targeting demersal fish, and characterised by area and mesh size classes (Storr-Paulsen *et al.*, 2012). Derogations have been granted every year since 2008 in the North Sea for two small fisheries targeting respectively sole and turbot, with relatively low landings (less than 300 t annually) and discards (DTU-Aqua *et al.*, 2011).

ii. Data analysis

The discard data from observers at sea was tested as a source of data to describe catch of landed and discarded individuals in the bottom set nets Danish fisheries, investigate the effects of gear and operational tactics on discard ratio and establish the relative contribution of different discarding drivers (**Paper II**).

iii. Limitations and further improvement

Stratification into métiers is a major issue regarding the bottom set nets fisheries: there should be enough groups to illustrate properly the diversity of the practices, but not too many so that there are enough data per strata. There have already been some thoughts about the topic, e.g., merging métiers in Skagerrak and Kattegat, or not merging them in the North Sea, but no proper analysis (DTU-Aqua *et al.*, 2011). For example, three métiers are currently sampled in the North Sea, based on mesh size, i.e., <120mm, 120-220mm and >220mm, but with no distinction between gear, i.e., gill- or trammel nets, and target species (Storr-Paulsen *et al.*, 2012). One could expect differences between gill- and trammel nets due to the higher variety of capture mechanisms associated with trammel nets, but these effects could not be looked at due to a low number of observations after subsetting the data to avoid confounding effects (Rubin, 2008; Nikolic *et al.*, 2015). The low number of observations for some of the strata sampled by the observers at sea for bottom set nets, together with a large variability in the data, provides with small power to investigate fine scale effects of catch pattern and discarding practices.

As the MLS has remained the same through the years of interest for the regulated fish species (1998-2016, Paper **II**), making assumptions on the proportions of discards below MCRS under the landing obligation was rather safe. But regarding quota restriction, the implementation of ITQ have most likely changed fisher tactics with a yearly quota attribution, giving more chance to fishers to optimize their catch on price rather than on quota as before. However, most of the sampling effort for observers on bottom set nets was concentrated in the late 90's, which leave the scientist with the insoluble choice between a less representative case study – also because the natural state has changed - with enough observations, or a more recent and representative case study but with a very low number of observations. Focusing all sampling effort in the next few years on species and/or fisheries with the most concern should be considered instead of a low sampling effort in all initially designated métiers if one needs to explore further the catch pattern and discarding practices under the new landing obligation.

B. Standardize different fishing efforts

1. Experimental set-up representative of commercial conditions

Running an experimental trial allows the scientist to be able to standardize the observations, which can be handy in the bottom set net fisheries to avoid the challenge of having to compare catch from nets of various types, length, soak durations. In **Papers I** and **III** for example, fleets of identical characteristics, with only soak duration as a varying factor, were used. But even with an experimental set-up, great care should be taken to be as representative as possible to commercial conditions, e.g., in the choice of net type and dimensions, or the way the net is soaked. It can therefore be very helpful to run experimental trials onboard a commercial vessel, so that the fisher can participate in the choice of the fishing grounds for example, ensuring optimum catches (Stergiou *et al.*, 2002), or reproduce commercial handling practices, which are of importance in particular regarding catch damage (**Paper III**).

2. Catch comparison analysis

We used a general analysis method that estimates the relative catch efficiency between two different designs of a fishing gear developed by Herrmann *et al.* (2017) (**Paper I**).

3. Discard ratio

Discards can be standardized per target species (Depestele *et al.*, 2012), per net length and soak time (Gonçalves *et al.*, 2007), per net number (Perez *et al.*, 2005), or by using the discard ratio (Rochet and Trenkel, 2005). The discard ratio is the ratio between discard and total catches, and may be computed for individual species or combined groups of species (Kelleher, 2005). Discard ratios, by including the landed portion of the FO, are inherently standardized to a wide range of effort variables, e.g., gear type, mesh size, net length or soak duration (Paradinas *et al.*, 2016) (**Paper II**).

C. Adjust to specificity of the data

Most of the previous studies regarding bottom set nets have been using hypothesis testing which does not allow for the estimation of the size of effects, unlike model-based methods, among which mixed modelling allows to include random effects to tackle the issue of pseudo-replication. Not all response variables have a normal error distribution, especially in our field of interest, with, e.g., count with number of individuals, proportions with discard ratio, or ordinal categories with catch quality, calling for the choice of a suitable distribution for the response variable, to appropriately model the data.

1. Specificity of bottom set nets data

i. Multi-model inference to account for (double) bell shaped selection curve in catch comparison

The method developed by Herrmann *et al.* (2017) and used in **Paper I** accounts for multiple competing models to describe the data using multi-model inference, and let us run catch comparison analysis in bottom set nets, independently of the shape of the selection curve - known to usually show a (double) bell shaped selection curve in bottom set nets(Millar and Fryer, 1999; Burnham and Anderson, 2002).

ii. *Catch damage index to assess fresh fish quality*

In the coastal fishery, fish is usually landed less than one day after capture and freshness, i.e., age of the raw material, which is usually perceived as the most important attribute of the quality of fish, is not appropriate (Denton, 2003; Esaiassen *et al.*, 2013; Martinsdóttir *et al.*, 2003). Instead, semi-quantitative indices of individual fish condition grouped in an index can be used to evaluate whole or processed fish damage in fishing gears (Depestele *et al.*, 2014; Digre *et al.*, 2010; Digre *et al.*, 2016; Karlsen *et al.*, 2015; Olsen *et al.*, 2013; Rotabakk *et al.*, 2011) (**Paper III**).

2. Specificity of response variable

i. Beta distribution for discard ratio

Discard ratios are measures of proportions which can take any continuous value ranging between 0 and 1, and can appropriately be described by a beta distribution – assuming that a transformation is applied for the two extremes, i.e., 0 and 1. Proportions are commonly used in descriptive studies, but the lack of available software to handle such data has restricted the uptake of the beta distribution for statistical regression. Instead, other response variables have been used, e.g., discard per unit effort, which might not be as appropriate here as discussed previously. Discard ratios have recently been modelled using beta distribution in a Bayesian hierarchical model by Paradinas *et al.* (2016). Instead, a beta distribution in a likelihood based approach was used with the newly developed open-source software R package glmmTMB (Magnusson *et al.*, 2017) (**Paper II**).

ii. *Cumulative link mixed modelling for ordinal multi-category responses*

The degree of fish damage was assessed using scores for different attributes ranging from 0 for flawless to 2 for most severe, known as an ordinal response. Again, choice of an appropriate distribution for the response variable is important. Cumulative link mixed modelling were used for such ordinal multi-category responses as they have shown to work well for sensometric data (Christensen and Brockhoff, 2013) (**Paper III**).

3. Inclusion of random effects

The random effect of, e.g., fleet or FO or vessel, is added to the model to avoid pseudo-replication by accounting for mechanisms that could generate positive association among clustered observations (Fryer, 1991; Millar and Anderson, 2004). For example, vessel was included as a random effect in **Paper II** to account for potential sources of variation on discards due to differences among vessels such as a skipper effect or unobserved gear characteristics. In addition to the use of random effects to account for within-fleet or FO or vessel correlations, fleet was also used as a random effect in **Paper III** to deal with scoring subjectivity, i.e., there may be differences in the assessment when all fish in a fleet are in similar condition or when they show a broader range of damage severities (Benoît *et al.*, 2010).

In catch comparison analysis, the between and within fleet variation was also accounted for by simulating multiple samples directly from the observed data in a double bootstrapping method. Between-fleet variation in the availability of fish and catch efficiency was accounted for by randomly selecting *aq* and *bq* fleets from the pool of fleets of soak patterns *a* and *b*, respectively (initial resampling). Within-fleet uncertainty in the size structure of the catch data was accounted for by randomly selecting fish from each fleet, with a total number of fish similar to that sampled in the fleet (bootstrapping of the initial resampling) (**Paper I**).

Additionally, one should keep in mind the relatively low number of observations per FO, e.g., compared to a commercial haul in active gear fisheries, due to the capture process of passive gears, which influence the total sample size available for analysis and therefore the number of potential covariates that one can look at.

- ✓ The limited information on passive gears is partly due to historical focus on active gears, but also because data collection and analysis calls for the development of appropriate innovative assessment methodologies to properly assess the new type of information which has to be gathered as part of an EAF.
- ✓ A stereo imaging method to assess in-situ the dynamic behavior of passive gears was identified, adapted, tested and used.
- ✓ Comparing bottom set nets fishing operations can be challenging as the measure of fishing effort depends on gear and fishing operation characteristics. We can work with experimental data in a controlled sampling design, but key information also comes from commercial observations. Statistical methods that have recently been developed were identified and used for estimating the relative catch efficiency between two different designs of a passive fishing gear or to standardize data.

III. CATCH PATTERN

Part 1 - Catch pattern (overview)

A. Species composition

1. Few different species caught by plaice gillnets in the Skagerrak

All species are not equally vulnerable to the gear, and bottom set nets can catch various species (*Fig. 16*). We assessed the species composition of gillnets in the summer plaice fishery in the Skagerrak (**Paper I**).

2. Major findings

In the Danish summer plaice gillnet fishery, there were few different species caught. Plaice, dab and edible crab were the most abundant and the most commonly occurring species (*Fig. 17*).

Figure 17. Species relative abundance per fleet and species occurrence, i.e., very common (≥75%), common (50-75%), uncommon (25-50%) and rare (<25%) species, for bottom set nets soaked 12 hours at day (12hD) in the summer plaice fishery in the Skagerrak.

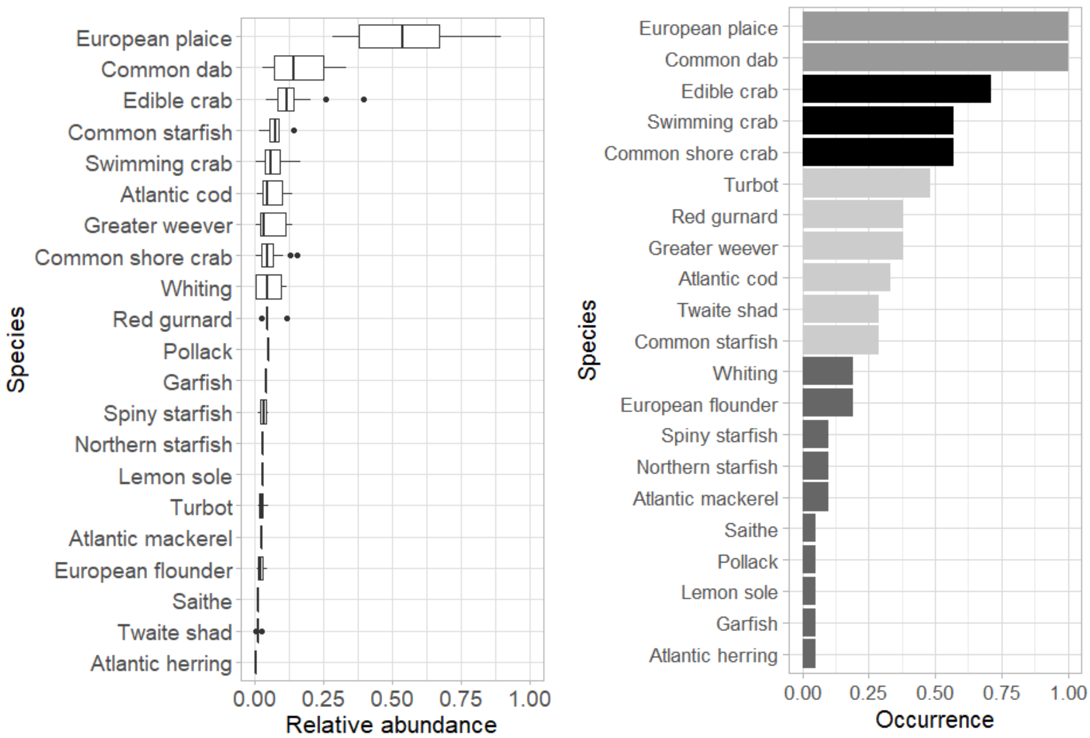


Figure 16. Catch from a gillnet in the Danish summer plaice fishery in the Skagerrak.

Figure 18. Edible crab entangled in the netting after passing through the drum of the hauler (right), individual untangled (middle left) and crushed (middle right), edible crab with shell crushed and missing legs (right)

3. In the perspective of the EAF

Experimental nets in the Danish summer plaice gillnet fishery were catching mainly benthic scavenging invertebrates, benthic feeding flatfish and fish species that eat small fish. The upper predators cod, saithe and pollack were caught in small numbers (*Fig. 17*). As the North Sea is dominated by small- and intermediate-sized species with correspondingly higher growth and reproductive rates (Rochet *et al.*, 2011), one should not expect drastic negative effects on natural populations.

4. Further development

Other gear types or fisheries, e.g., trammel nets or nets targeting the upper predator cod, may show a higher species diversity with a higher relative abundance and occurrence of the round fish.

Ultimately, the current debate on the overall objectives of an EAF, e.g., species selectivity versus balanced harvesting, make it difficult for gear technologists to develop further on the exact ecosystem effects of given fisheries.

B. Effects of gear design and operational tactics

1. Time of day and soak duration as key adjustable factors

Time of day and soak duration are easily adjustable factors and may play a key role in the gillnet fisheries. Previous studies suggested no relationship between soak time and catch size for soak durations longer than 6 hours (Acosta, 1994; Gonçalves *et al.*, 2008; Hickford and Schiel, 1996; Losanes *et al.*, 1992; Minns and Hurley, 1988; Rotherham *et al.*, 2006; Schmalz and Staples, 2014), but others proposed that there could be a decrease in catch rate with longer soaks as the net becomes more noticeable with the struggling of fish trying to escape and a repelling effect due to the smell of spoiled or dead fish, or space limitation in the net (Kennedy, 1951; Gonçalves *et al.*, 2008; Prchalova, 2013). On the other hand, longer soaks may increase the chance of scavengers and predators, and especially invertebrates, to be attracted by spoiled or dead fish in the net (Gonçalves *et al.*, 2008). Some species may be more likely to be present at day or at night regarding their daily rhythm, such as scavengers and predators which are more likely to be active at night (Hickford and Schiel, 1996).

We investigated the selective potential of three different soak patterns, i.e., 12h at day, 12h at night and 24h, in the Danish summer plaice gillnet fishery (**Paper I**).

2. Major findings

On average, there were about 1.5 more catches of the target species plaice with commercial size (above 27cm), and 2 and 4 times less catches of the unwanted dab and edible crab, respectively, for 12h at day compared to the other soak patterns (12h at night and 24h). It is in the gillnetter's interest to adopt a soak tactic that maximize the catch value by balancing ambient catch levels and handling time for the deployed gillnets. Gillnetters participating in the costal summer fishery for plaice can maximize their catch by catching more plaice at commercial size when they are more available to the gear, and limiting handling time by catching less dab and crabs when they are less available to the gear, i.e., during 12h at day.

3. In the perspective of the EAF

The landing obligation is meant to eliminate discards by promoting more selective fishing, ideally not just for commercial species (E.U., 2013). Avoiding unwanted bycatch, i.e., dab and crabs here, would also benefit the ecosystem approach. This is especially relevant if one question the survivability of discards released at sea – providing that they are not covered by the landing obligation. Dab were observed to be more prone to damage than plaice, and thus more likely to be released dead. Most of the crabs were crushed or had their legs removed by the fishermen to facilitate disentanglement from the net (*Fig. 18*).

Whereas operational challenges are expected for trawlers to avoid large bycatches in the context of the landing obligation, as it is already in the gillnetters' interest to limit unwanted catch, it is not expected that the landing obligation will favour another soak pattern or more generally drastic changes in fishing tactics in the summer plaice fishery.

4. Further development

Our experiment was designed to reproduce commercial practices in the summer plaice gillnet fishery in the shallow Skagerrak fishing grounds, for which the soak tactic is governed by edible crabs. Other patterns may be expected in other fisheries, seasons or areas.

Part 2 - Minimize unwanted catch

A. Discard ratio in North Sea cod, plaice and sole fisheries

1. A high variability in discard ratios for bottom set nets

The high variability found in discard ratios of several passive fisheries (*Table 5*), even using the same gear and in adjacent areas, reflect the versatility of nets and indicate the need to evaluate discards for each fishery (Gonçalves *et al.*, 2007; Batista *et al.*, 2009; Morandeau *et al.*, 2014).

Table 5. Discard ratio in number (DRnr) and weight (DRw) found in different studies across the world for gill (G) and trammel (T) nets, based on commercial (C) or experimental (E) data, with in brackets the number of fishing operations (FO) accounted for. Depth of the FO is given in m. The studies accounted for (Focus) fish (F), and/or mega-invertebrates (I), and/or other components, e.g., habitat formers, birds and mammals (All[1]), or birds and tortoises (All[2]). Discard ratios are given for all individuals, and/or target species [T], non-commercial species [NC], invertebrates [I], crabs [Cr], or others [O]. Variability for the last study was due to a difference in mesh size of the gears used (*).

Gear	Location	Depth	Exp (FO)	Focus	DRnr	DRw	Reference
G	Atlantic, France	-	C (27)	F	30 (0-50)	11	Morandeau *et al.*, 2014
T	Atlantic, France	-	C (27)	F	70 (10-88)	53	Morandeau *et al.*, 2014
G	Pacific, Mexico	-	C (30)	All[1]	45	34.3	Shester and Micheli, 2011
T	Atlantic, Portugal	10-100	C (37)	I, F	52.8	21.9	Batista *et al.*, 2009
T	Atlantic, Portugal	10-90	E (40)	I, F	74 (±8), 48 (±14) [I]	-	Gonçalves *et al.*, 2008
T	Atlantic, Portugal	15-100	E (40)	I, F	49.4	-	Gonçalves *et al.*, 2007
T	Atlantic, Spain	20-80	E (49)	I, F	22.3	-	Gonçalves *et al.*, 2007
T	Atlantic, Spain	10-30	E (60)	I, F	31.4	-	Gonçalves *et al.*, 2007
T	Aegan sea, Greece	10-80	E (41)	I, F	14.7	-	Gonçalves *et al.*, 2007
G	Atlantic, Brazil	132-607	C (14)	I, F	6.1 [T], 22.2 [Cr], >75 [O]	-	Perez and Wahrlich, 2005
G	Tasman Sea, Australia	-	C (265)	All[2]	6.2	3.3	Gray *et al.*, 2005
G	Atlantic, Portugal	500-700	E (20)	I, F	-	42 [T], <3 [NC]	Santos *et al.*, 2002
T	Atlantic, Portugal	<30-200	C (11)	I, F	-	0.13	Borges *et al.*, 2001
G	Aegan sea, Greece	4-90	E (42)	I, F	4.9-8.1*	2.9-7.3 *	Stergiou *et al.*, 2002

Discard ratios of the regulated fish species under the landing obligation, i.e., cod, haddock, sole and whiting, were described for the Danish bottom set nets fisheries targeting cod, plaice and sole in the North Sea (Paper **II**).

Over-quota and undersized discards were shown to be minor in other bottom set nets fisheries, but not all species or quality conditions have commercial value and can therefore also be discarded (Borges *et al.*, 2001; Santos *et al.*, 2002; Kelleher, 2005; Gonçalves *et al.*, 2007; Batista *et al.*, 2009; Morandeau *et al.*, 2014). As different discarding behavior may call for different mitigation measures, the discarding drivers in the Danish North Sea bottom set nets were explored. The relative contribution of different discarding drivers was established for each regulated species in all three fisheries using a hierarchical decision tree (Paper **II**).

2. Major findings

Discard ratios ranged from 1.10% for cod in the cod fishery to 100% for whiting in the sole fishery, with high variability between fishing operations, species and fisheries.

High-grading and catch quality were the main reasons for discarding observed in the cod and plaice fisheries, and catch of undersized individuals due to the use of small mesh sizes was the main challenge identified in the sole fishery.

3. In the perspective of the EAF

If the species is included in the landing obligation, it has to be landed, with no or uncertain economic value for the fisher, and will contribute to the same extent as commercially fit individuals to an EAF, i.e., removal of biomass from the ecosystem.

Bio-economic impact assessments performed on several North Sea mixed-fisheries fleets highlighted the impact of choke species, where the early TAC exhaustion of the least productive stock, e.g., cod, sole, whiting or turbot, or of a stock with limited historical fishing rights, e.g., hake, could lead to fishery closure and under-exploitation of the more productive stocks (Ulrich *et al.*, 2016). Such an effect in the bottom set nets fisheries is however expected to be relatively limited with the yearly quota attribution by the means of ITQ now in use in the Danish demersal fishery, together with the ability for netters to target different fish species throughout the year with limited discards for some of the fisheries.

Estimating discard patterns by fishery is of prime importance for mixed fishery models which are becoming more and more important for the biological advice to the different management authorities.

4. Further development

The low number of observations for some of the strata sampled by the observers at sea for bottom set nets, together with a large variability in the data, provides with small power to investigate fine scale effects of catch pattern and discarding practices. Focusing all sampling effort in the next few years on species and/or fisheries with the most concern should be considered instead of a low sampling effort in all initially designated métiers if one needs to explore further the catch pattern and discarding practices under the new landing obligation.

B. Effects of gear design and operational tactics

1. Choice of target species, fishing ground and soak duration are key to limit discards

Danish bottom set netters in the North Sea target successively plaice, sole and cod throughout the year, depending on the season. If small mesh sizes, i.e., less than 120mm, are used in the sole fishery, identical gear and mesh sizes can be used in the cod and plaice fisheries, yet resulting in the preferred catch of the target species and different discard ratios. Discards are highly variable in time and space, as local species diversity, season, depth or weather conditions are known to affect catch composition (Gray *et al.*, 2005; Stergiou *et al.*, 2002; Gonçalves *et al.*, 2007; Cambiè *et al.*, 2010). It was also suggested to reduce nets soak time in order to minimize the amount of damaged fishes (Acosta, 1994; Borges *et al.*, 2001; Gray *et al.*, 2005; Gonçalves *et al.*, 2007; Batista *et al.*, 2009; Cambiè *et al.*, 2010; Savina *et al.*, 2016). The effect of different explanatory variables on the discards in the Danish North Sea bottom set nets fisheries were explored (Paper **II**).

2. Major findings

Depth, year, soak time and vessel were more important in determining discard ratio for cod in the North Sea cod fishery than latitude and longitude, with an increased probability of cod discard with shallower waters.

3. In the perspective of the EAF

In general under the new landing obligation, the industry has not faced any major issue in fisheries using full mesh sizes between 130 and 200mm, e.g., the cod and plaice fisheries, as there are typically little discard (Chairman of Hirtshals fishermen organization, *Pers. Com.*). It was shown that fishers can adjust their strategy to limit the amount of unwanted catch (Paper **I**). However for fisheries using smaller mesh sizes between 80 and 120mm full mesh, e.g., the sole fishery, fishermen are facing larger bycatch of the round fish cod, haddock, saithe and whiting, and have started to change their tactics with the new landing obligation which could be described as a “real time monitoring” of discards: several fleets are soaked in the same time, one being lifted at regular intervals to check for the amount of unwanted catch (Chairman of Hirtshals fishermen organization, *Pers. Com.*).

4. Further development

The difficulty of reducing discards due to limited size selectivity in the small mesh sizes fisheries without impairing the catch of the target species has been acknowledged in the discard plan by granting to bottom set netters catching sole a minimis exemption up to a maximum of 3% of their total annual catches of sole. Considering a higher sampling effort for species and/or fisheries with higher concern, e.g., the sole fishery, one could also assess potential mitigation measures by testing for the effects of, e.g., fishing grounds or time of the day, on discards. Indeed, as sole is given high value on the markets, one strategy may be to find tactics limiting bycatch of the other species, even if the later would result in lower catch of the target species.

One could consider a modified stratification sampling scheme for the observers programme adapted not only to the mesh size of the FO, but also representative of the other characteristics defining the fisheries, i.e., gear and target species.

Part 3 - Maximize wanted catch

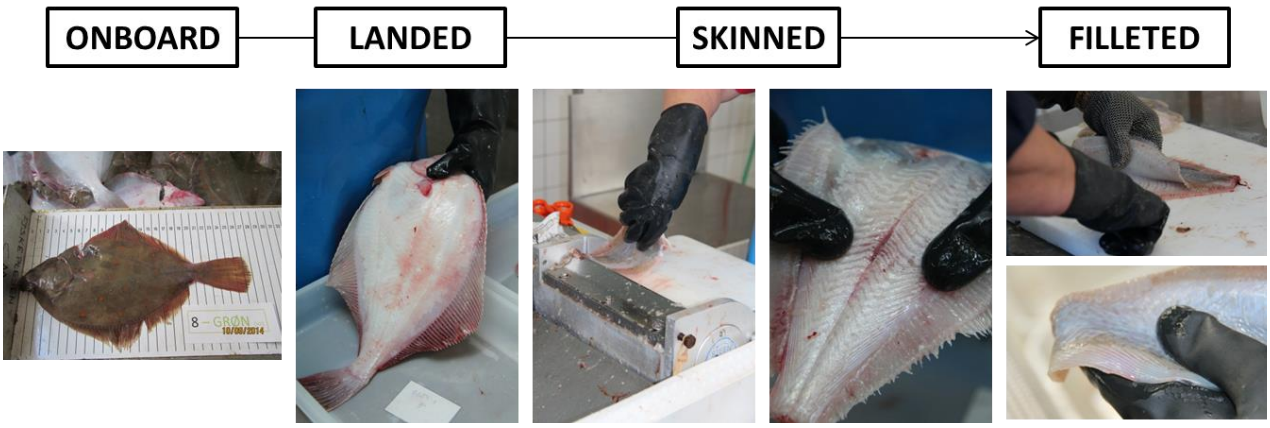
A. *Catch damage in the Danish bottom set nets fisheries*

1. Catch of bottom set nets is prone to damage due to its operation

Challenges in nets are that fish can die in the gear when the net is soaked, the netting can cause marks on the fish skin, and there is an increased risk of injuries due to predation or scavenging of fish in the gear (Auclair, 1984; Perez and Wahrlich, 2005; Petrakis *et al.*, 2010; Santos *et al.*, 2002; Suuronen *et al.*, 2012).

Damages in plaice captured with commercial gillnets were assessed using semi-quantitative indices of individual fish condition gathered in a Catch-damage-index (CDi) for onboard fish and a Processed fish-damage-index for whole, skinned and filleted plaice processed at a land-based factory (*Fig. 190*) (**Paper III**).

Figure 19. Assessment of whole, skinned and filleted plaice onboard the vessel and at land-based factory.



2. Major findings

Most of the assessed fish (99%) presented moderate or severe damage for at least one attribute. The CDi scores observed ranged from 0 to 9, i.e., none of the fish scored in the highest rating categories (10-12). The proportion of fish grading for score 2 at the attribute level were low except bruises, for which 40% were found in the body part. Bruises are a result of an accumulation of blood residue appearing as dark patches on the blind side of flatfish as a result of meshing, the fact that the fish struggled in the net, and handling (Botta *et al.*, 1987; Özyurt *et al.*, 2007).

Overall, gillnets delivered good quality fish (Susanne Kjærgaard Majid, Keka Fisk ApS, *pers. com.*). Damage in fish was significantly more likely for whole than filleted fish, but there was substantial heterogeneity among fish. Severe damage in whole fish may not matter in filleted fish, e.g., yarn marks and scale loss, whereas some damage may only be visible at the fillet level, e.g., severe gaping and jellied condition.

3. In the perspective of the EAF

Catch quality was observed as one of the main discarding drivers in the cod and plaice fisheries (Paper **II**).

Regarding socio-economic consequences, even if gillnets were able here to deliver good quality fish, prices for plaice in Denmark are in general low and show little variation, therefore calling for an additional change to better catch quality, e.g., new marketing opportunities such as direct sale.

4. Further development

Other more fragile species, e.g., round fish or dab, were observed to be more prone to damage than plaice, but catch numbers were too low for a detailed analysis. Further investigations could look into the differences between fish species, the factors responsible for the between-fish random variation, and the effect of different handling practices (vessel effect).

B. Effects of gear design and operational tactics

1. The controllable parameter soak time matters on raw material quality

Among the parameters that matter on the quality value of the raw material such as environmental variations or handling and storage methods, capture procedure, especially soak time, is a controllable parameter (Esaiassen *et al.*, 2013; Olsen *et al.*, 2014; Özogul and Özogul, 2004; Özyurt *et al.*, 2007). It might be an advantage to soak for long time periods to maximise catch per unit effort in some fisheries, but previous experiments have shown that the proportion of dead fish and degree of damage increase with soak time (Acosta, 1994; Hickford and Schiel, 1996; Hopper *et al.*, 2003; Petrakis *et al.*, 2010; Santos *et al.*, 2002; Suuronen *et al.*, 2012).

The effect of soak time on the degree of whole fish damage in plaice captured with commercial gillnets soaked for 12 and 24 hours was investigated (**Paper III**).

2. Major findings

Damage in fish was significantly more likely for longer soak times. Longer soak extended the probability for a caught-fish to be rubbed against the netting and show gear damage (93% for 24h and 85% for 12h) and skin abrasion (60% and 54%), with scale loss damages mainly located in the surroundings of yarn marks and associated with gear damages. Biting (43% and 34%), mostly located on fins and tail (96% of the damaged fish), was caused by scavengers and predators which had an increased chance to feed on the caught-fish at longer soak (Auclair, 1984; Perez and Wahrlich, 2005; Petrakis *et al.*, 2010; Santos *et al.*, 2002). Pressure damages (31% and 23%) were a result of the fish being squeezed close to the pelvic fin when the fisherman untangled it from the net (*Fig. 5*), which severity was expected to depend on mesh size and twine characteristics of the net, but could also be facilitated in damaged fish, i.e., those soaked for 24h. Overall effects were comparable to those of fish length and between-sets.

3. In the perspective of the EAF

Catch quality was one of the main reasons for discarding observed in the cod and plaice fisheries. With the landing obligation, discard of regulated species due to catch damage is not allowed anymore, therefore calling for solutions to improve catch quality in order to limit economic loss for the fisherman, quota deduction among others.

4. Further development

The effect of soak time on catch damage is expected to be higher for longer soak durations or more fragile species. Further investigations could look into the factors responsible for the between-fleets random variation.

- ✓ The selection properties of bottom set nets may be improved by changing the gear characteristics, but in many cases the fisher's operational tactic plays a preponderant role.
- ✓ One can intend to minimize the catch that is unwanted, or to maximize the part of the catch that is wanted.
- ✓ By adjusting their soak tactic, i.e., 12h at day, fishers participating in the costal summer fishery for plaice can maximize their catch by catching more plaice at commercial size when they are more available to the gear, and limiting handling time by catching less dab and crabs when they are less available to the gear.
- ✓ High-grading and catch quality were the main reasons for discarding observed in the cod and plaice fisheries, and catch of undersized individuals due to the use of small mesh sizes was the main challenge identified in the sole fishery. In the North Sea cod fishery, there was an increased probability of cod discard with shallower waters.
- ✓ Damage in fish was significantly more likely for longer soak times in the plaice fishery. With the optimum soak time, gillnets could deliver good quality fish.

IV. SEABED EFFECT

A. In-situ quantification of bottom-set gillnets movements on the seabed

1. Gear components in contact with the seabed

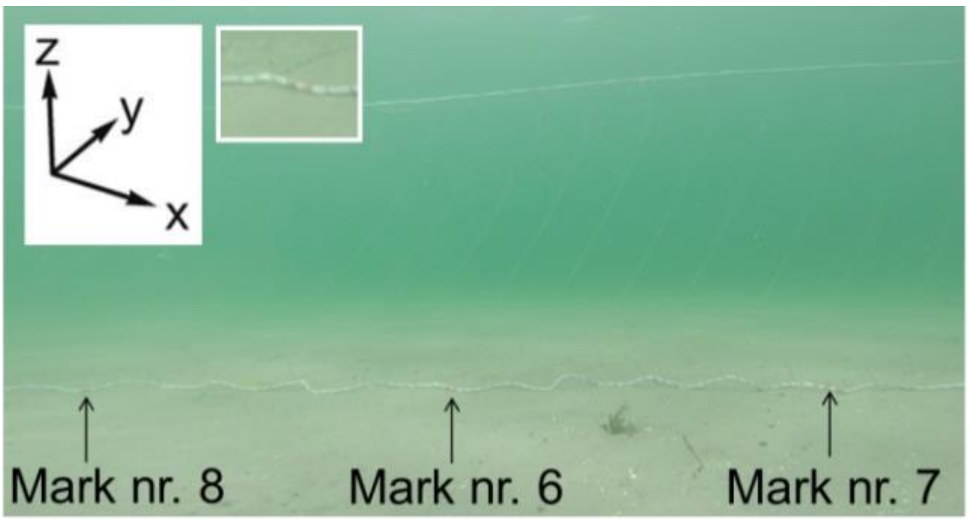
In bottom set nets, the gear components in contact with the seabed are the leadline, the anchors and the bridle lines (connecting the anchors to the gear). Nets may be dragged on the seabed and become tangled in bottom features as the gear moves with currents or turbulence, or may be snagged on benthic structures/organisms during retrieval of the gear (Shester and Micheli, 2011).

An in-situ gillnet experiment was carried out by adapting a stereo imaging method to the Danish coastal plaice fishery to assess the dynamic behavior of the leadline, i.e., the sweeping motion on the seabed and the penetration into the sediment (**Paper IV**).

2. Major findings

The leadline of bottom gillnets, fully deployed on the bottom, could sweep the seabed in sandy habitats up to about 2 m, ranging from 0.10 to 1.10m and 0.06 to 2.01m respectively in the X and Y dimensions (*Fig. 20*). Movements were the largest in the backward-forward dimension, which corresponded to the main direction of both the current and the waves in the experiment. The in-situ measurements of the leadline showed that movements were the smallest in the upward-downward dimension, ranging from 0.02 to 0.30m. The leadline was moving but not penetrating into the seabed, downward movements being most likely due to slight disparities in the seabed features.

Figure 20 Net fully deployed on the seabed – partly reproduced from *Savina, E., Krag, L.A., Madsen, N. Developing and testing a computer vision method to quantify 3D movements of bottom-set gillnets on the seabed. ICES Journal of Marine Research, 2017, fsx194, https://doi.org/10.1093/icesjms/fsx194*



The measured movements were representative only to a certain point of what really happens: as the nets were getting too far from or too close to the recording unit, it was not possible to take measurements anymore. Besides, current speeds during data collection were lower than the average range in coastal Danish waters. The present measurements of the movement of the leadline were therefore underestimated. However, the movement of the leadline was not unlimited as the fleets were anchored on the bottom.

3. In the perspective of the EAF

In terms of seabed disturbance, this means that the physical disruption of the seabed (penetration) of gillnets is minimal. The mechanism at stake is therefore partly different from that of active fishing gears, for which the habitat physical impact is partially due to seabed penetration (Eigaard *et al.*, 2016; Depestele *et al.*, 2016).

However, due to the sweeping movements, the leadline and netting could have potential direct damage to the benthos by snagging and entangling available entities. If we consider that a maximum of 30 km of nets are soaked in a typical bottom-set gillnets fishing operation (Montgomerie, 2015), we can roughly estimate the swept area to about 0.04 km^2 for light nets and 0.01 km^2 for heavy nets (based on a rectangle area calculation using the average measured range per mark in the Y dimension), which is much lower than any of the hourly swept area estimated for active fishing gears by Eigaard *et al.* (2016).

4. Further developments

The dynamic behavior of the leadline was analysed using a simple motion metrics in the three spatial dimensions, i.e., the maximum movement of the leadline in each dimension, but it would be interesting to further assess the nets behavior using our recordings of the spatio-temporal positions, e.g., with a spatio-temporal trajectory analysis.

Fishing gear disturbance is likely to have a more significant impact if it exceeds natural disturbance (Kaiser *et al.*, 2002). For example, shallow tide-swept and wave-impacted sandy habitats exhibit faunal communities that are well adapted to high rates of natural disturbance (Kaiser, 1998). Methods to further assess in-situ direct benthos damage by coupling mechanical to biological effects would give a more informative input in an EAF perspective.

It was difficult to draw a clear relationship between the nets and the current speed and direction. The complex effects of water flow, waves and wind, can change at a small scale, and influence the behavior of the gear (Shimizu *et al.*, 2004). These local differences in water flow could be a reason for the significant interacting effect of runs. Detailed measurement of the current direction and speed, e.g., using a current meter, in further experiments could provide with a better understanding of the environmental variables at stake.

Experiments were conducted in very shallow waters, which were needed to test how to operate the camera cages, also because water was turbid at the time of data collection. On the condition that an improved method allow to record in turbid waters, e.g., the previously mentioned adapted time-of-flight camera, further estimations should be run in deeper waters for which water flow conditions would be different as the turbulent boundary layer does not occupy the entire water column contrary to shallow waters (Soulsby, 1997; Otto *et al.*, 1990).

Observations only covered the soaking phase of a gillnetting operation, i.e., when the gear was fully deployed on the bottom, and not the retrieval of the gear, therefore not covering the total potential habitat effect of bottom gillnets. Shester and Micheli (2011) as well as Sørensen *et al.* (2016) observed the entanglement and removal of flora by set gillnets while being hauled. Effects of hauling are more likely to be destructive as more power is exerted through the nets (hauler) than when soaking, for which, e.g., a stone could eventually stop the net. It is however known from fishermen practices that the way the gear is handled when hauling can significantly reduce possible habitat damage, e.g., hauling in the current direction.

B. Effects of gear design and operational tactics

1. Gear characteristics and rigging play a key role in the net behavior

The gear characteristics and rigging specifications play a key role in the net behavior, and therefore its potential seabed effects. The internal force acting on the netting is not homogenous over its entire surface, with stronger force close to where the head- and leadlines are attached (Takagi *et al.*, 2007). Water flow pushes the netting to incline and bulge out of the vertical plane, lowering the headline height (Stewart, 1988; Takagi *et al.*, 2007). Shimizu *et al.* (2007) calculated that the leadline would slide across the sea bottom if the force acting on the leadline is larger than the coefficient of static friction, but sliding motions of bottom gill nets during fishing have not been directly observed in any study to our knowledge.

Two different types of commercial bottom gillnets, light and heavy, were used to give a gradient of commercial conditions. All nets were commercial plaice gillnets, and heavy and light nets differed only in the specifications of the head- and leadlines. The headline was different for the two gear types as it influences the inclination of the net and has commonly more buoyancy for heavier nets in commercial conditions (**Paper IV**).

2. Major findings

The gear configuration affected the sweeping of the nets, with light nets moving significantly more than heavy ones. Whereas the general perception is that heavy gears are more destructive to the habitat, such as in active gears (Kaiser *et al.*, 2002), it was demonstrated here that a heavier leadline would result in less movement, being the actual issue in terms of potential habitat damage of bottom-set gillnets. Therefore, gear configuration has a strong mitigation effect regarding the sweeping behavior of the leadline, and habitat damage could be reduced by using heavier nets.

3. In the perspective of the EAF

Bottom set nets frequently fish in areas where fishing with active gears is limited due to technical limitations in the use of the gear, e.g., in reef areas, which also happen to be the most commonly designated sites for conservation protection, e.g., under the Habitats Directive (Natura 2000 sites) (Sørensen *et al.*, 2016). The observed effects of each individual FO may be negligible, but the cumulated effects may be of importance at the scale of the fishery, especially if it is concentrated in particularly sensitive habitats.

Regarding the consequences for a potential change in net configuration, i.e., light versus heavy nets, on the fisher gains, light nets fish better as they have more slack, and potentially thinner twine diameter, but fall down and have reduced catch if the current is too high. In addition, lighter nets are more prone to damage and therefore need to be changed more often.

4. Further developments

In addition to the tested net configuration, i.e., light and heavy nets, other components of the fishing gear in gillnets could be looked at to mitigate their habitat effects. Bridles attached to either the head or bottom line will give the netting different types of curves which will affect the drag (Stewart and Ferro, 1985). The netting hanging ratio and length of fleets, as well as the way the nets are set out could also affect the leadline movement of bottom-set gillnets. In addition to the leadline, it was shown that the anchors could have an effect while hauling the gear (Sørensen *et al.*, 2016).

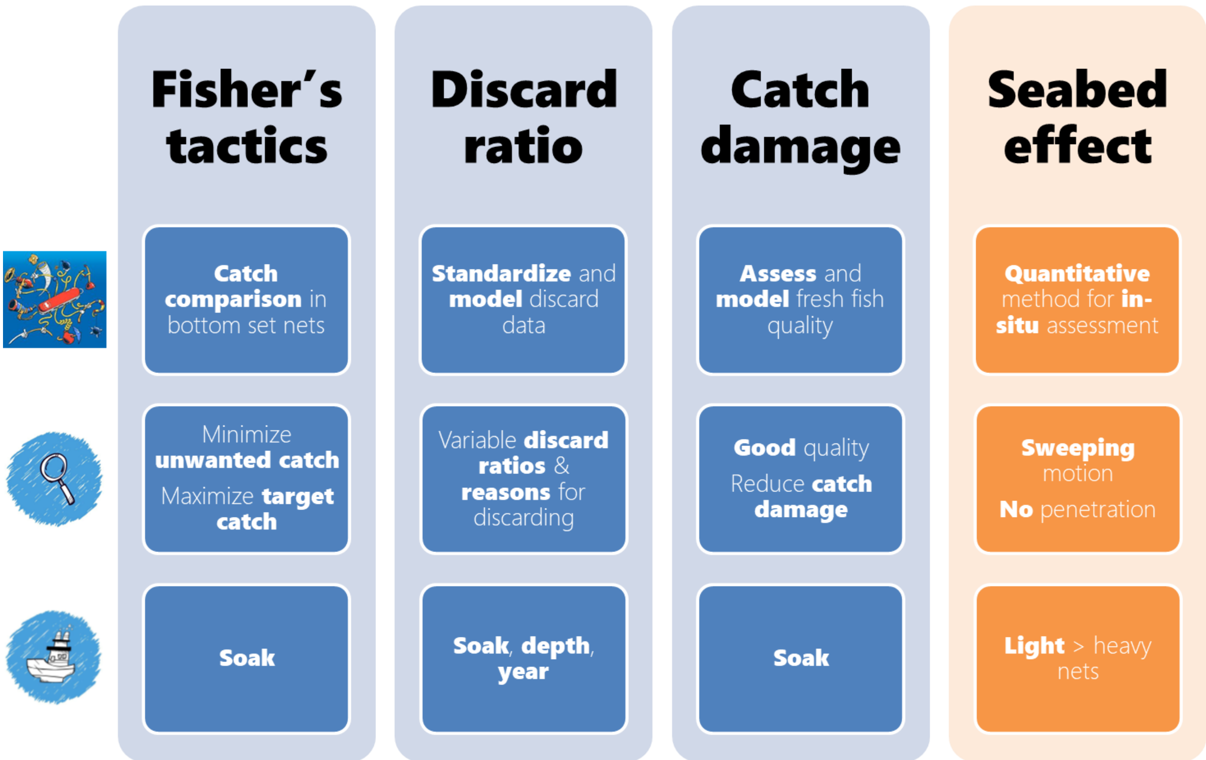
- ✓ The direct physical disruption of the seabed of gillnets was minimal as the leadline was moving but not penetrating into the seabed.
- ✓ The sweeping movements could be up to about 2m, but resulted in a total swept area per fishing operation lower than any of the hourly swept area estimated for active fishing gears.
- ✓ Whereas the general perception is that heavy gears are more destructive to the habitat, it was demonstrated here that light nets were moving significantly more than heavy ones.

VI. SUMMARY OF THE FINDINGS & FUTURE PERSPECTIVES

A. Summary of the findings and implications for the net fisheries

The Danish bottom set nets observed in the present work were able to select a limited number of species and a high fraction of marketable fish. In addition to the gear characteristics, fisher's tactics were shown to play a key role in the catch pattern, due to the fact that it is in the fisher's interest to adopt a tactic that maximize the catch value by balancing catch levels and handling time for the deployed nets (*Fig.* 21). Changes in operational tactics, e.g., soak time, is a powerful tool to limit unwanted catch, which can be use by the net fisheries to adjust to the landing obligation.

Figure 21. Summary of the findings



The direct physical disruption of the seabed was minimal as the leadline was not penetrating into the seabed. Whereas the general perception is that heavy gears are more destructive to the habitat, light nets were moving significantly more than heavy ones (*Fig.* 21). The expected changes in the rules governing access rights may create a major incentive for the industry to adopt gears that provide more fishing opportunities. In that respect, bottom set nets could play a key part, for example by being potentially compatible with restricted protected areas providing that gear design, e.g., heavy instead of light nets, is taken into consideration as mitigation measure. Bottom set nets are also likely to be compatible with other activities, e.g., offshore wind farms as the risk of hooking cables is negligible (no seabed penetration).

B. Future perspectives

Gear technologists have started to describe fishing pressure on community components, e.g., species composition, while comparing gears or fishing tactics. We can work with experimental data in a controlled sampling design, but key information also comes from commercial observations. However, because the observers at sea sampling plan was not designed for that purpose, the reduced number of observations and specific stratification allow to highlight some behaviour but not to extrapolate results, and impose to analyse some potentially confounding factors together, which might mask some effects and ultimately bias the analysis. In addition, assessing fishing pressure on community components require further information on the natural populations. Scientific trawl surveys, e.g., the International Bottom Trawl Survey (IBTS) in the North Sea, can be considered in some cases as a potential proxy for the community species composition. Scientific surveys give density estimates, which can be difficult to compare with passive gear fishing effort, but methods have recently been developed to standardize metrics for comparing fishing operations from different gears (Fauconnet *et al.*, 2015). However, sampling locations of the trawl survey are not always spatially and temporally concurrent with coastal bottom set nets fisheries, for technical reasons, e.g., not possible to trawl in rocky areas. As the EAF brings new demands to the scientific community, one might question the relevance of the content and stratification of the current European sampling data schemes.

Besides, for many of the potential fishing effects, the current scientific understanding does not allow to establish a clear relationship with fishing pressure, particularly regarding the effects on biogeochemical cycling or ecosystem resilience and functioning. It seems more and more relevant to support interdisciplinary research projects for coupling mechanical and biological effects of fishing on the ecosystem.

In addition to fishing pressure, fishing intensity has also to be accounted for. This is not always easy for fleets with relatively small vessels such as in the Danish gill- and trammel nets fisheries, because they do not all have high resolution spatial data. One alternative could be to work with stakeholders including fishers through interviews for a mapping of fishing hot spots and marine habitats.

Ultimately, management will influence the adoption of one gear towards another, thus discouraging or encouraging conservation goals, and will likely play a key role in the next few years on the development or on contrary the decrease of the Danish bottom set nets fisheries. The current allocation of specific quotas to coastal fisheries might beneficiate to the Danish gill- and trammel netters. Further development of netting practices could for example include the promotion of the opportunity of daily fresh fish supply by the coastal vessels, as selling whole fish directly to consumers has proven worthy for some Danish coastal gillnetters, e.g., the established and successful network http://havfriskfisk.dk/default.asp for the very small vessels. Then, improvement in whole fish quality could therefore make a difference.

Regarding the possibility to fish in restricted sensitive areas, further studies should be conducted on the effect of the sweeping behavior of the leadline (and anchors) on the benthic flora.

The reductions in fishing effort mean that natural mortality is becoming a major source of mortality in the North Sea, and the stock dynamics are increasingly influenced by natural processes and not by fisheries only (Ulrich *et al.*, 2016). Besides fishing effects on the ecosystem, it is necessary within an EAF to consider the effects of the environment on fisheries (Jennings and Revill, 2007). For example, the development of fisheries that are able to adapt to climate change and rising oil prices might be supported, among which bottom set nets are known to be fuel efficient (Jennings and Revill, 2007; Suuronen *et al.*, 2012). The increasing seal populations, however, and particularly the grey seal population in the Baltic, are forcing fishermen to stop use gillnets and switch to, e.g., trawling, or leave the fishery.

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Paper I

Effect of fisher's soak tactic on catch pattern in the Danish gillnet plaice fishery

Savina, E., Krag, L.A., Frandsen, R.P., Madsen, N.

*Fisheries Research, 2017, **196**, 56-65.*

Abstract

Soak duration in the gillnet fisheries can vary from a few hours to several days. The industry reports a variation of soak tactics between target species, but also between seasons for the same species. These are determined by the robustness of the target species and the catch of unwanted species. Different soak tactics were compared to estimate the role that the choice of a soak tactic plays in the catch efficiency of both target and unwanted species. In the Danish summer gillnet fishery targeting plaice *(Pleuronectes platessa)*, nets are deployed approximately 12 hours (h) during day. Unwanted species are common dab (*Limanda limanda*) and edible crab (*Cancer pagurus*). The commercially used 12 h deployment during day was compared to 12 h deployment during night and 24 h deployment. On average, there were about 1.5 more catches of commercial size plaice (above 27cm), and 2 and 4 times less catches of the unwanted dab and edible crab, respectively, for 12 h at day compared to the other soak tactics (12 h at night or 24 h). Gillnetters participating in the coastal summer fishery for plaice follow the theoretical optimal soak tactic. The commercially used 12 h deployment during day maximises the catch of commercial sized plaice and limits handling time by catching less unwanted dab and crabs.

Paper II

Discard of regulated species under the landing obligation in the Danish bottom set nets fisheries for cod, sole and plaice in the North Sea

Savina, E., Krag, L.A.

Manuscript

Abstract

This study aimed at (1) describing discards of regulated fish species under the landing obligation, i.e., cod, haddock, sole and whiting (2) investigating the effects of soak duration, depth, latitude and longitude on discards and (3) establishing the relative contribution of different discarding drivers for the regulated species in the Danish bottom set nets fisheries for cod, plaice and sole in the North Sea using the discard data from observers at sea. We used discard ratio to standardize bottom set nets data, and a beta distribution to model cod discard ratio in the cod fisheries. Discard ratios ranged from 1.10% for cod in the cod fishery to 100% for whiting in the sole fishery, with high variability between fishing operations, species and fisheries. The relative contribution of different discarding drivers was established for each regulated species in all three fisheries using a hierarchical decision tree. High-grading and catch quality were the main reasons for discarding in the cod and plaice fisheries, and catch of undersized individuals due to the use of small mesh sizes was the main challenge identified in the sole fishery. We showed that the use of a beta distribution provided with an easy approach to further explore the effects of potential explanatory variables on discard ratios. We found that in the North Sea cod fishery, there was a decreased probability of cod discard with depth, with greater effect in the more recent years.

Paper III

Testing the effect of soak time on catch damage in a coastal gillnetter and the consequences on processed fish quality

Savina, E., Karlsen, J.D., Frandsen, R.P., Krag, L.A., Kristensen, K., Madsen, N.

*Food Control, 2016, **70**, 310-317.*

Abstract

This study aims at testing how to improve catch quality aboard a coastal gillnetter by looking at an easily controllable parameter known to have an effect on the degree of fish damage, soak time, and investigating if the registered damages on whole fish have an effect on processed products such as fillets. Plaice (*Pleuronectes platessa*) was captured with commercial gillnets soaked for 12 and 24 hours. Damages were assessed using semi-quantitative indices of individual fish condition gathered in a Catch-damage-index for onboard fish and a Processed fish-damage-index for whole, skinned and filleted plaice processed at a land-based factory. Cumulative link mixed modelling allowed the estimation of the size of effects. Damage in fish was significantly more likely for longer soak times but effects were comparable to those of fish length and between-sets, making a change in soak time not so substantial for improving plaice quality in coastal gillnetting. Damage in fish was significantly more likely for whole than filleted fish, but there was substantial heterogeneity among fish. Severe damage in whole fish may not matter in filleted fish whereas some damage may only be visible at the fillet level.

Paper IV

Developing and testing a computer vision method to quantify 3D movements of bottom-set gillnets on the seabed

Savina, E., Krag, L.A., Madsen, N.

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Abstract

Gillnets are one of the most widely used fishing gears, but there is limited knowledge about their habitat effects, partly due to the lack of methodology to quantify such effects. A stereo imaging method was identified and adapted to quantify the dynamic behavior of gillnets in-situ. Two cameras took synchronized images of the gear from slightly different perspectives, allowing to estimate the distance from the observation unit to the gear such as in the human 3D vision. The sweeping motion on the seabed and the penetration into the sediment of the leadline of light and heavy commercial bottom gillnets deployed in sandy habitats in the Danish coastal plaice fishery were assessed. The direct physical disruption of the seabed was minimal as the leadline was not penetrating into the seabed. Direct damage to the benthos could however originate from the sweeping movements of the nets, which were found to be higher than usually estimated by experts, up to about 2 m. The sweeping movements were for the most part in the order of magnitude of 10 cm, and resulted in a total swept area per fishing operation lower than any of the hourly swept area estimated for active fishing gears. Whereas the general perception is that heavy gears are more destructive to the habitat, light nets were moving significantly more than heavy ones. The established methodology could be further applied to assess gear dynamic behavior in-situ of other static gears.